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Polymers and Cross-Linking: A CORE Experiment To Help Students Think on the Submicroscopic Level

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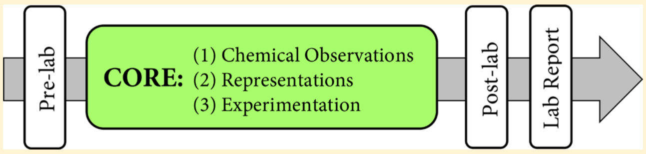
Supporting Information

ABSTRACT: The Polymers and Cross-Linking experiment is presented via a new three phase learning cycle: **CORE** (**C**hemical **O**bservations, **R**epresentations, **E**xperimentation), which is designed to model productive chemical inquiry and to promote a deeper understanding about the chemistry operating at the submicroscopic level. The experiment is built on two familiar activities often used in public outreach: mixing solutions of poly(vinyl alcohol) and sodium borate, producing the substance known as "slime", and linking paper clips as an analogy to represent polymers. In phase 1 of the **CORE** experiment, students prepare slime, and explore the properties of the separate solutions and slime. In phase 2, students use analogical reasoning to think about a representation for considering the chemistry at the submicroscopic level. The analogy activity includes using an Analog to Target Worksheet to carefully consider similarities and differences between the analog (paper clip chains) and target (polymers). Phase 3 begins with pairs of students designing experiments in response to this question: How do different proportions of the two reactants, poly(vinyl alcohol) and sodium borate, affect the material properties of the new polymer that is formed? In a recent JCE paper, we report the capacity for students to engage in using analogical reasoning when conducting the Polymer and Cross-Linking experiment. In this paper, we include an analysis of a postlab question, asking students to propose an alternative analogy that could be used in the lab experiment. Detailed analysis of a subset (23 out of 312) of student-generated alternative analogies is provided in Supporting Information. Together with the previously published paper, the data provides insight into student thinking about using analogical reasoning in the Polymers and Cross-Linking **CORE** experiment.



KEYWORDS: *First-Year Undergraduate, Laboratory Instruction, Analogies/Transfer, Inquiry-Based Learning, Constructivism, Hands-On Learning/Manipulatives*

INTRODUCTION

This paper describes the Polymers and Cross-Linking experiment, which introduces the **CORE** approach and was recently used as the context of research to explore students' capacity to engage in using analogical reasoning.[1] The experiment is built upon two familiar activities often featured in chemistry public outreach events: mixing solutions of poly(vinyl alcohol) and sodium borate to produce the substance known as "slime" and linking paper clips to represent polymers. We chose these familiar activities to introduce a new laboratory instructional strategy, called **CORE**, which was designed to scaffold a deeper understanding of the particulate nature of matter.[2,3] **CORE** experiments are organized into three phases in which students make *chemical observations* (phase 1), explore a *representation* using analogical reasoning (phase 2), and design *experiments* (phase 3). The **CORE** learning cycle is designed to model for students the process of productive chemical inquiry, in which a chemist makes initial observations, analyzes the results by considering what is occurring at the submicroscopic scale, and advances the inquiry by proposing further experiments to probe understanding at the submicroscopic scale. One of the motivations for using **CORE** in introductory laboratory instruction is that analogical reasoning is essential for thinking at the submicroscopic level (i.e., atomic-molecular scale).[4,5]

In developing **CORE** experiments that feature an analogy,[6] we considered best practices to help students use analogical reasoning appropriately. These include the following: the analogy should connect a domain that is familiar to the student (the analog)[7] with a domain that is sufficiently demanding (the target); similarities (correspondences) and limitations (where the analogy breaks down or fails) should be explicitly considered; and the analog and target should share deeper structural similarities, not merely surface features.[8−10] This paper presents a description of the Polymer and Cross-Linking lab procedure, with an emphasis on how the **CORE** strategy is used to promote analogical reasoning in this lab experiment. It

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also presents an analysis of student generated alternative analogies that provides additional insight into their analogical reasoning skills. The student lab procedure, instructor notes, and additional information related to student-generated alternative analogies are provided in Supporting Information.

LAB PROCEDURES

Overview

The structure of the **CORE** approach is modeled on the process of doing science and thinking about submicroscopic level phenomena. In lab, students have an opportunity to make observations, think about an explanation for the observations using analogical reasoning, and then design experiments to test their ideas about what is occurring at the submicroscopic scale. Explicit consideration of the limitations in analogical models is a key feature of the **CORE** approach and is incorporated as a strategy to reduce misconceptions. Providing students with a macroscopic model of the chemistry occurring at the submicroscopic level offers an opportunity to make accessible abstract reasoning, which many students find exceedingly difficult.[2,11−14]

Students are required to complete prelab activities to prepare for the lab and also to engage in postlab group discussions with the lab instructor and other students. Following completion of the lab, students prepare lab reports, which provide details about their experimental data and the scientific arguments that can be built from the data. Since the Polymers and Cross-Linking lab experiment occurs near the beginning of the semester, students are provided with guidance on writing a lab report, and this rubric is also included in the lab materials (see Supporting Information). Four additional **CORE** lab experiments have been developed to date, in which students explore paper chromatography, conservation of mass, limiting reagents, and UV−vis spectroscopy.

Developing the Experiment

The Polymer and Cross-Linking lab experiment has been student tested at the University of Maine with more than 3,500 students over the past six years. Modifications to the lab experiment have been made on the basis of various assessment strategies, including student responses to online pre- and/or postquestions, interviews,[15] and discussions with graduate student chemistry lab instructors. Students work in pairs during the 3 h lab period, and there are 16 students in each lab section. Laboratory instructors take part in a 1 credit graduate-level course once a year, which is taught by one of the authors (MB) and covers active learning strategies, including inquiry-based instruction, as well as relevant literature readings and discussions relating to chemical education theory and practice.

Slime and Paper Clips as a Teaching and Learning Activity

Making slime is a popular, public outreach activity that is frequently employed to encourage people to have fun with chemistry and help them think about chemical reactions, the properties of chemicals, and in particular polymers. The instructions for making slime from materials like poly(vinyl alcohol), white glue, and borax (also known as sodium borate), have appeared in the literature and online.[16−18] The mechanical and thermal properties of poly(vinyl alcohol) cross-linked with borax were reported in 1976,[19] and this mixture's non-Newtonian flow was discussed in *Scientific American* in 1978.[20]

In the Polymers and Cross-Linking experiment, students explore the material properties of slime[17,21] by mixing solutions of poly(vinyl alcohol) and sodium borate. Although slime is often perceived as a simple substance, the cross-links between borate and poly(vinyl alcohol) involve a complex, dynamic equilibrum,[19,22,23] which has been the subject of recent chemical research exploring the various proposed structures of PVA−boric acid.[24]

Paper clips have been used as physical models,[25] and for thinking about molecular weight averages of polymers.[26] Several instructional analogies have been introduced to model the process of polymer formation and cross-linking. For example, a classroom activity in which students line up and link arms to represent polymers and then link arms across two chains of students to represent cross-linking has been previously reported.[27] Paper clips have also been used to model the reaction of poly(vinyl alcohol) and sodium borate in the middle-school inquiry-based science activity in SEPUP (Science Education for Public Understanding Program).[28] An activity using paper clips to teach polymer basics has been described,[29] which includes information that instructors can use to discuss the limitations of the paper clip model. However, student consideration of the limitations of the model is not presented as an essential feature of the model building activity. This is a common deficit in curricula that use analogies, despite research indicating that a key aspect of effective teaching with analogies is explicit consideration *by students* of how the analogy breaks down.[30−36] This is the reason that **CORE** experiments are designed to provide opportunities for students to generate *their own* critiques of analogical models of submicroscopic level phenomena.

The analogy activity in the Polymers and Cross-Linking experiment uses white and black paper clips, where white paper clips are linked together to represent poly(vinyl alcohol) and black paper clips represent borate. There are several unique features of the Polymers and Cross-Linking **CORE** experiment: (1) integrating chemical observations with the analogy activity, (2) student construction of the analogy through consideration of the similarities and differences across macroscopic and submicroscopic domains, and (3) students designing and carrying out experiments to follow up on these activities.

The choice to provide a concrete analogy (paper clips) to introduce the **CORE** learning cycle is part of a conscious decision to make the analogy more accessible,[37−39] especially when students are developing skills with analogical reasoning. More abstract analogies and other forms of analogical reasoning (e.g., a simulation) may follow in subsequent experiments, after students master the elementary skills of analogical reasoning.

Prelab Preparation and Prelab Discussion

Prior to performing the lab experiment, students download introductory materials, including instructions for the experiment, by using InterChemNet, a web-based management program.[40] The introductory materials describe the **CORE** learning cycle, the motivation for the approach, and some information about analogies. Students are required to complete a prelab assignment, which consists of writing a brief introduction, creating a chemical safety table, and answering several questions about analogy and the nature of scientific inquiry.

At the beginning of the lab period, lab instructors meet with their sections to facilitate discussion of the prelab assignment and draw attention to specific features of the lab. Prior research has shown that familiarity with the analog is an important consideration in having students understand an analogy.[8,14]

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Table 1. Student Observation Examples about Similarities and Differences across Domains[a]

Analog to Target Comparison	White Paper Clip Chains Compared to Polyvinyl Alcohol	Black Paper Clips Compared to Sodium Borate	The Action of Linking White Chains with Black Clips Compared to the Chemical Reaction	The Product of Linking White Chains Together with Black Paper Clips Compared to the Slime Product
Similarities: What characteristics does the analog share with the target?	Long, linear repeating chains; PVA is composed of repeating monomers; white paper clip chains are composed of repeating units; PVA runs through the funnel easily and similar to the how the paper clips run through the funnel.	Black clip is single unit; borate is relatively small, singular molecule.	Black clips link white chains together.	White chains linked with black clips often have difficulty passing through funnel.
		Black clips and solution of sodium borate both easily flow through funnel.	Sodium borate chemically links (interacts) chains of PVA.	Slime does not flow through funnel easily.
Differences: How does the analog not accurately represent the target?	PVA is actually a very much longer chain than the paper clip model we assembled in lab.	The size of the black paper clips ($\approx 2.5 \times 10^{-2}$ m) compared to the size of sodium borate ($\approx 2.5{-}10\times 10^{-10}$ m) is enormously different!	The paper clips are physically clipped together.	In slime, the links are constantly made and broken, but the paper clips stay firmly attached to one another.
			The PVA chain is held together by bonds between monomers and the borate chemically interacts with the PVA (i.e., cross-linking).	

[a]Students use the Analog to Target Worksheet.

Thus, during these discussions, students are encouraged to reflect on their familiarity with the properties of the analog: in this case linking paper clips together as representations of polymers.

Phase 1: Chemical Observations

Following the prelab discussion, students move into the lab to prepare slime and conduct several simple tests on the physical properties of slime. For example, students test the flow characteristics of slime, and compare it to the solutions of poly(vinyl alcohol) and sodium borate by pouring each solution through a plastic powder funnel. Pouring slime through a powder funnel takes some time, and some students will conclude that this step can be skipped. However, unless they actually test it, these students will only have an assumption to consider, rather than data. During phase 1, students also make observations to allow them to determine the density of slime (in g/mL), and the densities of the solutions of poly(vinyl alcohol) and sodium borate. Students discuss several open-ended questions, make some drawings, and make a prediction to elicit thinking at the macroscopic and submicroscopic scales; examples include the following:

- Predict what you think will happen when you combine the two solutions.
- Draw a picture of how you imagine the reaction to occur at the molecular level.
- How does the figure you have drawn explain your observations of the macroscopic (visible) properties of the slime?

Students record answers in their lab notebooks, and lab instructors look for evidence that students are reflecting on these questions by examining the carbon copies of their lab notebooks, which are turned in at the end of lab. The observations made in lab and questions posed in the lab procedures are designed to prompt students to think about the chemistry at the molecular scale. However, as noted in the cognitive sciences,[41] and from laboratory activities,[11] students do not often spontaneously make connections between macroscopic and submicroscopic phenomena. Thus, while guided inquiry in phase 1 provides an opportunity for students to link their laboratory observations to the molecular scale, the analogical reasoning activity in phase 2 is designed to help them explore these connections more thoroughly to deepen their understanding.

Phase 2: Representation

For this phase, the activities shift out of the lab to the adjacent "breakout" room where students consider the analogy, which is designed to help them think at the submicroscopic level about the chemistry they have just performed in the lab. The analogy involves connecting chains of white paper clips (representing poly(vinyl alcohol)) with black clips (representing sodium borate) and experimenting with a powder funnel (to explore structure−property relationships). The activities in phase 2 are designed to parallel those in phase 1 in order to convey higher order relations and promote deeper understanding of analogical processes in phase 1 and phase 2. The meaning of the paper clip analogy in regard to poly(vinyl alcohol) and sodium borate solutions focuses on how structure influences flow characteristics. Students "experiment" with passing the paper clips through a powder funnel, noting the flow characteristics of single clips or chains of white clips vs the chains linked with black clips.

Student construction of the analogy includes completing an Analog to Target Worksheet (see Table 1) in which similarities and differences between the analog (the familiar domain)[8] and target (the unfamiliar domain)[8] are explicitly considered by focusing on how the structure of the materials in each domain influences the properties of the materials.[9] The worksheet also includes a place for a molecular drawing to illustrate a 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. The lab instructor plays an important role in encouraging students to think at the molecular level, and to make comparisons between the macroscopic and submicroscopic levels.

During this phase, when students are asked to complete the Analog to Target Worksheet, they are guided to consider similarities and differences between the analog and the target. This is a strategy to support students in thinking about how chemical observations and the representations can be used to generate submicroscopic explanations for chemical phenomena. The range of student responses on the Analog to Target Worksheet is wide, and reveals a diversity of student thinking. Table 1 shows some examples of student observations (drawings are excluded). For example, in the paper clip analogy, the structural connectivity is conveyed by clipping white paper clips together to form a chain of clips, which corresponds to chemical bonds connecting monomers together

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to form polymers. Thus, consideration of the differences between analog and target should result in students explaining that paper clips are held together by physical means while the monomer units are held together via chemical bonding. A correspondence across domains (macro- to submicroscopic) is that units in each domain are attached but the mode of attachment is different, i.e., physical vs chemical. Student reflection on the limitations of the analogical model is critical in setting up a deeper understanding[38] and minimizing misinterpretations.[30−36] The structure−property relations invoked by comparison across domains encourage deeper thinking for the purpose of gaining insight into the *chemical observation* phase and preparing students to develop their own procedures in the *experimentation* phase.

Phase 3: Experimentation

Following completion of the analogy activities, phase 3 begins in the breakout room with pairs of students designing experiments to explore this question: How do different proportions of the two reactants, poly(vinyl alcohol) and sodium borate, affect the material properties of the new polymer that is formed? The process of designing an experiment is challenging for students who have previously only had explicit procedures provided in lab.[42] Accordingly, because this is the first **CORE** experiment that students encounter, we have provided a fair amount of support (i.e., instructional scaffolding) in this phase. For example, the directions contain the following advice:

> *Think carefully about how you will evaluate each sample of slime you create with different ratios of reactants. You can make qualitative observations (e.g., visible consistency, funnel flow patterns) or quantitative measurements (e.g., density, mass of excess reagent). Make sure that the data you collect will be convincing and stand up to scrutiny.*

Students discuss their experimental approach with one another, review their plans with the lab instructor, and then return to the lab to conduct their experiments. The instructor "signs off" on the experimental plan, acting as a gatekeeper to help students generate data to assess the scientific question. Instructors may alter the amount of scaffolding they provide, based on the level of experience students have had with inquiry-based instruction. Students summarize their experimental findings on a Designing Experiments Worksheet.

■ HAZARDS

Students should be warned not to ingest any of the materials. Sodium borate (borax) is toxic by ingestion: solutions and substances made of this material should not be ingested. In the prelab activity, students are required to look up the MSDS sheets of all chemicals, including recommended safety handling procedures. Goggles are mandatory in lab, and gloves are available for students wanting to use them.

■ STUDENT-GENERATED ALTERNATIVE ANALOGIES

One week following completion of the Polymers and Cross-Linking experiment, students were asked to respond to four questions online using InterChemNet.[40] In one of these questions, students were asked: "Is there another analogy that you can think of that would help you gain insight into the chemistry involved in this lab? Please explain." In a recently published study, data from this question were combined with student responses to the other three questions to score understanding of analogy (i.e., this question was not separately analyzed).[1] The study included details about connections to the macroscopic and submicroscopic parts of the analogy, appreciation of the limitations of an analogical model, perceived benefits, and reservations. Data were analyzed using a framework developed from structure mapping theory.[9] Results indicated that about 75% of students had a *basic or better* understanding of analogical reasoning according to this framework. Students who explained or described the analogy were judged to have a *basic* level of understanding of the paper clip analogy. A *better* level of understanding was demonstrated by explaining the analogy *and* making connections to their chemical observations in lab (macroscopic level), *or* to the submicroscopic level. Students were scored as having attained the highest level of analogical reasoning if their responses contained descriptions of the paper clip analogy in which they made connections between *both* the macroscopic and submicroscopic levels. In this paper, the data set from the question above about alternative analogies was analyzed separately to provide a greater depth of understanding about student thinking using analogical reasoning.

The paper clip analogy used in the Polymers and Cross-Linking experiment can be thought of as a concept building analogical model,[43] which is a type of representation. Providing students with an analogy (e.g., paper clips) followed by asking them to suggest alternative analogies, offers students the opportunity to reflect on their own analogical reasoning and the appropriate use of multiple representations. Harrison and De Jong have recommended "the use of multiple analogies",[36] Harrison and Treagust discussed the use of analogical models for representing molecules,[43] and Spier-Dance et al. reported the value of student-generated analogies in promoting conceptual understanding.[44] By considering their similarities, differences, and limitations, deeper conceptual understandings of closely related representations can be achieved.

The necessity of learning the appropriate use of multiple representations in chemistry is aptly illustrated by a familiar situation encountered in introductory chemistry courses where students are introduced to many different ways of representing molecules.[43] As an example, consider the various models of methane shown in Figure 1. Many examples of analogical models for methane are possible, including Lewis structures, ball-and-spring, wave function density, and X-ray structures, but the four representations shown are sufficient to illustrate the general usefulness of multiple representations for conveying somewhat distinct analogical information. For example, consider the ball and stick model in Figure 1d. If students are asked to provide an alternative representation, any of the other choices listed in Figure 1 is perfectly acceptable. However, if students are asked which alternative representation to Figure 1d also conveys information about the three-dimensional properties of methane, only Figure 1c (and not Figure 1a or Figure 1b) is acceptable. Further, distinct differences between Figure 1c and Figure 1d exist that are important for students to appreciate. For example, although

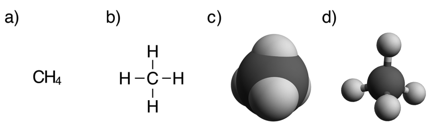

Figure 1. Multiple representations: analogical models used to represent methane.

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both Figure 1c and Figure 1d convey three-dimensional information, only the space-filling model in Figure 1c incorporates the more sophisticated idea of the shape of the electron cloud. The limitations of these analogical models are also important to focus on. For example, in Figure 1d, while a wooden stick is hard and has mass, the bond it represents is made up of forces with negligible mass and is polarizable to some extent. As with any analogical model, it becomes important for an instructor to explicitly point out the limitations in order to minimize alternative conceptions.

Analysis of Analogies Proposed by Students

The postlab question described above, which asked students to propose alternative analogies, was optional, and no course points were associated with responding. Yet, more than 60% of students (n = 312) submitted an alternative analogy. Analysis revealed that many of the alternative analogies employed similar objects. A total of 17 similar objects were used by 3 or more student-generated analogies (see Table 2). The objects included chains, people interacting, strings and ropes, magnets, interlocking building blocks, and ladders. Many of the student-generated analogies contained logic that paralleled the paper clip analogy. For example, 60 students utilized a funnel as an apparatus for testing, similar to the paper clip analogy. In these alternative analogies, students explained how objects could be connected together and that after connection, if they were tested in some fashion (e.g., with an apparatus), the assemblage possessed significantly altered properties compared to the separated objects.

Table 2. Similar Objects Used by Three or More Students in Student-Generated Analogies

Objects Used in Alternative Analogy	Students Using the Object, N
Funnel	60
Chains	58
Food	36
People interacting	34
Strings and ropes	22
Magnets	18
Interlocking building blocks	17
Ladders	16
Water	10
Traffic	10
Trains	8
Jello	7
Cement	4
Wood	4
Books	3
Velcro	3
Pipe cleaners	3

A set of 23 student-generated analogies was selected to represent a cross section of objects used by students (see Table 2 and Supporting Information). The set was analyzed to gain insight into how these student-generated analogies compared with the instructor-provided paper-clip analogy. The set illustrates the creative and diverse ways students go about using analogical reasoning to gain insight into chemistry involved in the lab. While the analysis shows that the student-generated analogies were not completely parallel in construction to the paper clip analogy, most contained essential analogical elements that would permit them to be refined (if students were asked to work with them further) into productive models. Finally, while most of the descriptions by students contain information about the similarities across dimensions, few mentioned the limitations of the models. This result provides more evidence that students do not spontaneously attend to the limitations of analogical models and emphasizes the importance of providing scaffolding for beginning students (e.g., incorporating use of the Analog to Target Worksheet) to develop the skill to consider both the similarities and limitations of an analogical model.

■ SUMMARY

The Polymers and Cross-Linking experiment is an introduction to the **CORE** (**C**hemical **O**bservations, **R**epresentations, **E**xperimentation) learning cycle, which is used to help students conduct productive inquiry and access submicroscopic thinking. The experiment involves two very familiar activities of making slime and linking paper clips as a representation involving monomers and polymers. During the experiment, students explore the properties of slime (phase 1), use white and black paper clips to think about representations at the submicroscopic level (phase 2), and then proceed to design and carry out experiments in response to a scientific question (phase 3). Postlab, students were asked to propose an alternative analogy that could be used in the lab experiment.

The benefits of using multiple analogical representations in classroom and laboratory activities are discussed. A postlab assessment is described where students were asked to provide an alternative analogy that could be used in the experiment. More than 60% of students submitted alternative analogies. An analysis of 23 student-generated postlaboratory analogies indicates that, although there is evidence of significant analogical reasoning, none of the 23 students discussed the differences between analog and target, or the differences between the proposed analogy and the original analogy. Though imperfect, most of the student-generated alternative analogies contained elements of analogical reasoning that would permit them to be refined as suitable alternatives in a follow-up activity.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.6b00010.

Details of the assessment of student-generated alternative analogies (PDF, DOCX)
Student laboratory procedures (PDF, DOCX)
Instructor notes (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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J. Chem. Educ. XXXX, XXX, XXX−XXX