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CourseSource

Lesson

Student-Generated Analogies for Learning about Information Flow

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Abstract

Using analogies is a standard practice for both teaching and communicating ideas in science. Here we upend the traditional lesson, where the instructor provides a fully constructed analogy and explains it, by having the students develop a complex analogy themselves. This high engagement, peer learning activity engages students in critical thinking and analogical reasoning to foster deeper understanding of molecular processes and their interconnection. In this lesson, groups of students are asked to relate given items to DNA and to decide which level it best represents (nucleotide, gene, chromosome, or genome). Next they are tasked with extending the analogy to include other actors in the central dogma of molecular biology (RNA, protein, polymerases, ribosomes, etc.), and then to extend it even further (introns/exons, mutations, evolution, etc.). Finally, each group presents their analogy to the class, and they evaluate each other. We provide multiple examples of items that can be used in the activity, but others can be identified with some creativity. This exercise is also an excellent tool for instructors to discover where their students have gaps and need help making connections to bridge their understanding of processes in molecular biology.

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Learning Goals

Students will:

◊ know the terminology for, as well as relationships and hierarchy of, components of biological information systems.

◊ gain a better understanding of how DNA acts as an information storage molecule, similar to other forms of information storage in non-biological contexts.

◊ gain a better understanding of how genetic information relates to cellular functions, organisms and species.

◊ From the Biochemistry and Molecular Biology Learning Framework:

» What is a genome?

» How does the nucleotide sequence of the gene lead to biological function?

» How do genomes transmit information from one generation to the next?

» What is the molecular basis of evolution?

◊ From the Genetics Learning Framework:

» How is DNA organized?

» What are the molecular components and mechanisms necessary to preserve and duplicate an organism's genome?

» How is genetic information expressed so it affects an organism's structure and function?

» How do different types of mutations affect genes and the corresponding mRNAs and proteins?

Learning Objectives

Students will be able to:

◊ create an analogy that incorporates multiple components of biological information systems, based on a familiar instructional item.

◊ build an extended analogy from the starting model that differentiates between different levels of organization of genetic information.

◊ critique an analogy that describes the relationship of DNA with information flow, exchange and storage.

INTRODUCTION

Teaching with analogies is a well-established strategy to help students understand complex processes in science (*e.g.,* [1]). An analogy is a type of model that involves mapping of a new idea to a familiar idea, and using the parallel structures to bring understanding of the familiar context to explain the new context (*e.g.,* arm is to hand as branch is to leaf). Typically, the teacher presents a well-developed analogy to the students, sets up the structure and then explains how each concept relates to aspects of the familiar scenario. In this activity, we have flipped the process so that the students are the ones to develop the analogy based on a familiar item. In this activity, students build a sophisticated, extended analogy to explain everything from genes to proteins to organisms and even evolution. By having students construct analogies themselves, we are activating their analogical reasoning skills. Analogical reasoning is a tool for higher order thinking, which is important for creativity, design, and problem solving.

One of the core concepts for biological literacy from *Vision and Change* (2) is the Central Dogma of Molecular Biology, which falls under the broader topic of "Information Flow, Exchange and Storage." The Central Dogma is a deceptively simple concept, but most students struggle to put all of the pieces together in a coherent way, as described previously (3, 4). Anecdotally, students often find the terminology difficult and have trouble differentiating between genes, genomes, DNA, RNA, proteins, and traits. Due to the difficulty students have with these concepts, many activities and lessons have been developed to teach students about Central Dogma concepts. Some examples include a clicker-based case that encourages students to compare and contrast molecular processes in the absence and presence of a mutation (5), a paper-folding activity to reinforce the relationship between DNA sequence (with and without mutation/recombination) and final products (6) and a lab-based activity to help students understand the difference between genes and gene expression (7).

While other published literature has focused on how to teach Central Dogma, the activity we present here aims to help students understand it in the context of cell biology and higher order biological processes, such as evolution. The inclusion of evolution as an extension of the Central Dogma distinguishes our activity from the previous literature and reflects the values of *Vision and Change* which emphasize the importance of understanding information flow across biological scales (8). We developed this lesson to allow students to practice higher order thinking about information flow and to give students an opportunity to grapple with the relationships between molecules and processes they have already learned about, to build a more solid foundation for future coursework. By creating analogies, students are synthesizing information and ideas in ways that allow them to practice higher-order skills of Bloom's Taxonomy. Creation is at the top of the Bloom's taxonomy pyramid, indicating that it requires the highest order cognitive skills (9), yet it is rarely used as a learning outcome in undergraduate courses (10, 11). The activity described here fills a gap in the Central Dogma literature by providing opportunities for students to extend their previously-learned knowledge about molecular processes and engage in the types of higher-order cognitive skills that are often overlooked in undergraduate biology instruction.

The idea of this lesson is deceptively simple: students are challenged to defend their conceptions of genetic terminology, processes, and concepts by developing complex analogies with familiar contexts (*e.g.,* cooking, music, theater, video games). For example, a group of students is given the sheet music for the song "Tomorrow" from the musical *Annie*. The first question students have to grapple with is whether the item best represents a nucleotide, a gene, a chromosome, or a genome. Note that this requires thinking about not just the item but also how the item relates to the overall context from which it was pulled (*e.g.,* a song produced from the sheet music and the entire musical). Once the group agrees on the starting structure, they are asked to identify other components of the Central Dogma within the same context of the analogy. Students must support their reasoning with evidence from the real world context as well as what they know about the biological concepts (*e.g.,* if the song is analogous to the protein, then what is the singer? Perhaps a ribosome). Students continue to extend the analogy as far as they can take it until it breaks down. This may require revision and debate within the group and critique from the instructor. When the group reaches a point where the analogy breaks down, this provides a place for students to practice other higher-order cognitive skills, such as evaluation. Students may evaluate the limitations of their analogy and where their analogy does not align with the underlying biological concepts. This may lead to debate and revision within the group to create a more refined and biologically accurate analogy.

We have identified many familiar objects that can be compared to genetic information (Supporting File S1). During class, students work in groups to build complex analogies starting with a familiar item, and they debate the details to deepen their understanding of genetic information storage and gene expression. Terms that are often conflated by students, such as "gene" and "trait," become real opportunities for reflection as students are forced to think carefully about their words and their own mental models of the Central Dogma. In addition to students practicing higher-order cognitive skills by creating and evaluating their own analogies, we extend this activity to have students evaluate the analogies created by their peers. By opening up the analogies for class debate, students may deepen their understanding.

Instructors can ask probing questions to gently push students to rectify their thinking by statements such as, "You said that the chapter on cakes (in the cookbook) was a genome. If one chapter was a genome, what does the entire cookbook represent?" Students might then correct their model and report that a chapter of a cookbook was actually a chromosome and the entire cookbook was the genome. Instructors can also challenge students who master a "basic" model to extend their analogy through questions such as, "What would evolution look like in this model?" or "In your model, what is natural selection?" or even "How would epigenetic changes be reflected in your model?" and "What about post-translational modification?" The possibilities of probing questions are nearly endless!

Students' choices often reveal what they think is the salient feature of a term, which may or may not align with its scientific meaning. For example, students often say that a mutation is a mistake such as adding the wrong amount of an ingredient,

which ruins the cake (student example from using a recipe as the item). This is not a good analogy, because making a mistake in translation is a transient change, not a permanent one. Thus, students have latched onto the idea of "error" without considering the level of the change (DNA or protein) or its context (permanence or reproduction of results). They have also demonstrated their assumption that mutations are always bad. Discussing mutation in this simple context allows them greater insight into the process and downstream effects of mutation.

Intended Audience

This activity was first developed for a second-year Cell Biology course and refined in an Introductory Biology course for majors at a large, private university. In both cases, it was implemented in a small class (up to 36 students) where the instructor was supported by a Learning Assistant (LA). It could be scaled up with the use of multiple LAs and not having all groups present to the entire class, but rather having a few groups present to each other. Additionally, this activity could be implemented in a recitation session or even in a laboratory session as a warm-up to a larger project about the Central Dogma. This activity could be used in any number of course in which topics involving genetic information flow are discussed, including advanced courses.

Required Learning Time

This activity was designed to be completed in one class period (approximately 75 minutes). The lesson could also be spread over two classes by allowing more time for development of their analogies and requiring more formal presentations on the second day (*e.g.,* a prepared slideshow). Alternatively, students could develop their analogies in class and share their work through an online forum with a homework assignment to comment on each other's ideas.

Prerequisite Student Knowledge

Unlike other activities about the Central Dogma (5–7), the point of this activity is not to introduce concepts or teach them for the first time. Students must be familiar with terms and processes linked with genetic information flow such as biological macromolecules, transcription, translation, gene structure, mutation, and evolution. In this activity, students are challenged to link these ideas together in a sophisticated way, which encourages them to think more deeply about spatial and temporal relationships of biomolecules and complex processes.

Prerequisite Teacher Knowledge

Instructors should have a solid understanding of the same topics related to genetic information flow. They should also have some idea of where potential misalignments are likely to happen. Shulman first recognized the importance of pedagogical content knowledge (PCK) for instructors to be able to effectively address student misunderstanding specific to the topics being discussed (12). We know that students come into biology courses with incomplete ideas and alternative conceptions about information flow (3, 13–15). Doing this activity can help reveal those ideas, so that the instructor can address them.

SCIENTIFIC TEACHING THEMES

Active Learning

The lesson revolves around students actively participating in cooperative group-based learning. The activity is generally too difficult for one student to complete on their own. This type of active learning has consistently been found to correlate with improved learning gains in numerous settings (16–18). The instructional staff provides gentle guidance and prompts participation by all group members to ensure all students are getting the maximum benefit from the activity.

Assessment

Table 1 shows how the materials generated through the activity can be used to assess student mastery of the learning objectives. Additionally, the process of students discussing the analogies and comparing ideas ought to help them discover what they do and do not know about the subject. Instructors listening to student discussions will also learn which concepts their students are struggling with (*i.e.,* formative assessment). Critiques are used to allow students to peer-review each other's work (Supporting File S2). Exam questions are provided to assess how well students have learned the practice of making analogies involving genetic information (Supporting File S3). Concept inventories such as the Introductory Molecular and Cell Biology Assessment (IMCA) (19) or the Central Dogma Concept Inventory (CDCI) (20) could also be used as a pre/post assessment to determine whether students improved their overall understanding of the Central Dogma and other molecular processes.

For instructors who would like to score the analogies, we offer a simple scoring rubric (Supporting File S4). Consider the following example, based on real student answers we have observed. Students are given a dictionary with the section of words beginning with "C" marked. As they develop their model, part of their analogy states that the entire dictionary is like a genome and the marked section is equivalent to a chromosome since a chromosome is a piece of the genome. Then they say that each word defined is like a gene, and that the letters of that word are equivalent to nucleotides. Finally, they propose that RNA would be analogous to synonyms of the word. We would score this group with a "3" (highest score) for their genome and chromosome components, because they make sense in terms of the biological functions as well as how they fit with other components. The RNA suggestion is incorrect in terms of both function (RNA contains the same information, not just the same meaning as the DNA it was transcribed from) and analogy (*e.g.,* RNA for a particular gene is not found elsewhere within the genome), so this component would get a score of "0." The gene and nucleotide components are more complex. A gene is made up of nucleotides, and the nucleotides are what provides the information to the gene, just as letters can be interpreted as words. However, nucleotides make up the entire genome, not just genes. In other words, while the function is correct, the analogy falls short because the relationship of the nucleotide to elements beyond the gene are lacking. Thus we would assign a "2" to the nucleotide component. On the other hand, the analogy of the gene does fall correctly within the hierarchy of genome > chromosome > gene > nucleotide, but it does not meet the function well since

the word alone does not provide information to do anything—it is the definition of the word that fulfills that role. Thus, we would assign a score of "1" for this component.

Inclusive Teaching

As long as students have some knowledge of genetic information flow, they can participate in the activity and have a meaningful experience. The lesson is an example of high intensity active learning, which has been shown to narrow achievement gaps for underrepresented students (21). It is designed to leverage diversity of student thought and experience. As they discuss the analogies, their differences in perspectives, ideas and backgrounds become apparent, and they need to work together to reconcile their differences. The items used for building analogies are drawn from different aspects of life outside of science (*e.g.,* music, cooking, theater, video games). Each individual has a different perspective to bring to the exercise from their own personal history, and working together in mixed teams will allow more creativity and insight. Low-stakes, high intensity, active learning strategies are more equitable and thus, help narrow achievement gaps for underrepresented students (22).

LESSON PLAN

A timeline for preparing and delivering the lesson is provided in Table 2.

Pre-Class Preparation

To prepare for class, you must first decide on the number of groups you will have. Ideally, each team will have a different item, although items can be repeated with larger classes or if the instructor only wants to have a small number of items circulating at one time. Groups of 3–4 are preferable for productive discussion, although larger and smaller teams could also perform well. In choosing groups, diversity of experience and ways of thinking is helpful to the creative process.

The activity requires household items which need to be sources of information used to create something. The nine different examples that have been tested with students are detailed in Supporting File S1. Our tested examples include: A section of Webster's Dictionary containing all the words that start with the letter "C," a page out of an address book, the song "Tomorrow" from the script of the musical *Annie Junior*, plus six additional items. Other ideas for this activity include: blueprints, maps, computer code, instruction manuals, and encyclopedias. Note that specific features of our examples may have been more relevant to our student population (*e.g.,* at our institution *The Harry Potter Cookbook* is helpful to opening conversation). Thus, we encourage you to choose items that are more personally relevant to students in the class—for example, a recipe from a Vietnamese cookbook, a song from *Hamilton*, a photomosaic of a culturally relevant person, place or icon.

If the physical items are available, label them with sticky notes that say "your item is…" (see Primary Image for the article). If you don't want to bring in the actual items or cannot find enough of them, create a page describing the item in words and/or pictures. For example, provide a photo of a set of encyclopedias with the heading "Your item is Volume G from the World Book Encyclopedia." We also suggest that different aspects of the various items be highlighted as the starting point to allow different groups to start with different levels (gene, chromosome, or genome). Each item should be able to cover all three, so if the same item is used with more than one group, different starting points should be used (*e.g.,* if the item of an encyclopedia is used for two different groups, one group should start by thinking about the entry for the word "giraffe" and the other group should start by thinking about Volume G of the entire set of encyclopedias).

Before class, you will need to print out one group worksheet per team (Supporting File S5) and one reflection sheet per individual (Supporting File S2). If students are to reflect on multiple analogies, print out additional reflection sheets.

During Class

Before passing out the materials, let them know that they will have 30 minutes to work on the activity with their group

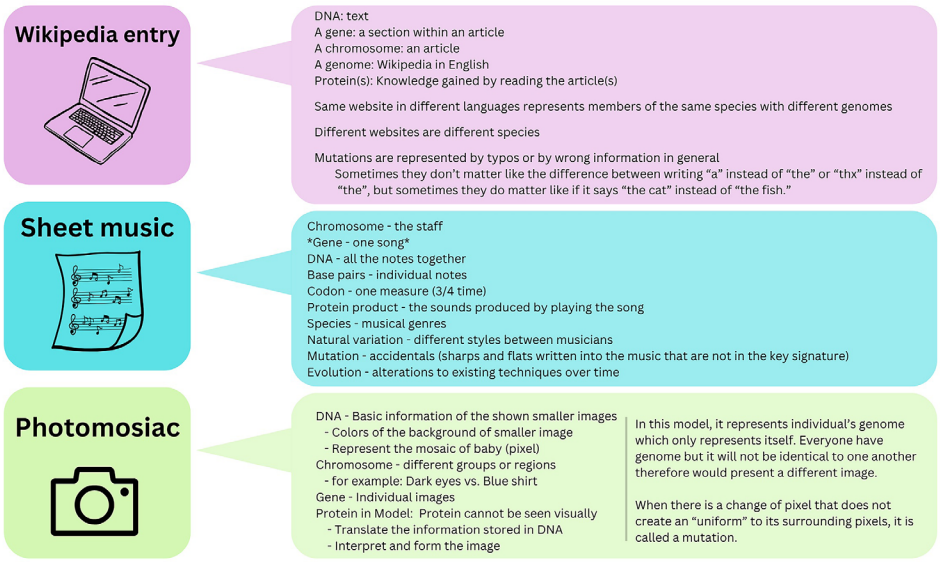

Figure 1. Examples of student work. Three different items (Wikipedia entry, sheet music, and photomosaic) were used as the basis of analogies by three different groups in a Cell Biology class. Written responses are transcribed verbatim here; student formatting is preserved as much as possible.

and then they will present their ideas to the class. The activity does not require much of an introduction. Tell the students that they will be doing a group activity where they will try to make an analogy between an item provided to them and DNA. Do not initially tell the students they will be building a complex analogy to describe information flow, as students may be overwhelmed at the beginning. Use your preferred method to set up groups of 3–4 before passing out the labeled items and the group worksheets (Supporting File S5).

Provide students time to examine their items and start brainstorming before beginning to advise/probe teams. If there are LAs or Teaching Assistants in the classroom, have them circulate the class as well to monitor groups. As students discuss, listen to their discussions and offer encouragement when they seem to be on a good track. If they seem to be having trouble or have selected a poor metaphor, offer some hints or guidance. It is often enough to just say, "why did you choose that?" or "why didn't you choose this?" It is important to make sure students can justify their choices. If students do not notice when they have a poor fit, be sure to hint or point out flaws in the metaphor and encourage them to rethink it.

After 20 minutes or so, students should have a fairly complete analogy (*e.g.,* Figure 1). Remind the groups that they will need to present their full analogy to the class, so they should plan how they are going to do that. Students will need to explain the item they were given as well as all the aspects of the analogy; they should plan for about a 3 minute presentation. In our experience, there is enough time to do presentations for 9 groups within the same 75-minute class period that the activity was introduced. If class times are shorter than 75 minutes, the presentations can be done in the next class period. In a large class with many groups, you could solicit volunteers, select groups to present theirs as examples, or have different sets of groups present to each other.

Assign each student to critique a different team's analogy. Pass out the individual reflection sheets (Supporting File S2), where they will record their thoughts. Call up each group individually to make their presentation. Encourage questions from the audience and ask a few yourself to model good practice. In particular, look for deviations from the suggested answers, probe students on how they came up with their ideas, and gently point out flaws in their logic. Remind students to fill out the reflection sheet, and collect them at the end of class.

A good critique might identify a facet of the analogy that does not mesh properly with the rest of the analogy. For example, if students are using the cake recipe, they might correctly align the recipe with a gene, a copy of the recipe on another piece of paper in shorthand notation as the mRNA, but identify the cake as the organism. A critique would point out that the cake should be the final gene product (protein), not the organism. Alternatively, the student might add something to the analogy that was missing in the original. For example, in Figure 1, the sheet music analogy does not include a ribosome. A student might extend the analogy to say that the people playing the music are like ribosomes because they "translate" the written symbols on the page to sound.

We view our analogy activity as a learning activity, not as a summative assessment. However, if instructors do wish to grade or score their students' analogies, they can use our suggested rubric (Supporting File S4).

After Class

We strongly suggest grading for effort rather than correctness. However, if summative grading is desired, we suggest that after class, students are given the opportunity to revise and resubmit their analogies based on feedback from their peers and instructors. Either way, an answer key (Supporting File S1) can be provided if desired for students to use as a study tool, with the preface, "Here are my thoughts on what would make the best analogy. These are not the only possible answers. Many of you had other ideas that were good! Note similarities and differences from your own ideas." Additional questions to assess learning, such as in a subsequent quiz or exam, are provided in Supporting File S3.

As the analogies are expanded on, the connections between the analogy and the biology become more nuanced, and there is the potential for disagreement in interpretation. Instructors may wish to ask students about their experience with the activity in order to determine how it helped them make connections between concepts or potentially even confused them.

TEACHING DISCUSSION

In our experiences, students are very engaged by the lesson. They struggle a bit with the first step, but most students can choose a good starting point with a little bit of effort. The extension of the analogies (thinking about evolution, mutation, ribosomes, etc.) is where students struggle more. When you hear flawed or incomplete ideas, try to point out where things don't quite work. For example, students often say that a mutation would be like making a mistake in measuring an ingredient for the cake or substituting an ingredient. You could ask, "Is that a permanent mistake? Will all cake products from this recipe now contain that same mistake, or did just one person make a mistake during one attempt at making a cake?" This type of probing helps learners see the difference between a permanent mutation that gets passed down to future generations (actual change in the written recipe) and a transient mistake in transcription or translation (the baker mistakenly measures incorrectly).

Sometimes students choose a poor starting point (like deciding an entire section of an address book is a gene instead of realizing one entry of the address book better represents a gene) and then struggle when extending the analogy because of the shaky foundation. Encourage them to rethink their model and revise as necessary. Students are often resistant to change their model, but don't let them see it as failure if their original model was faulty. The ability to think critically about what they have done and make revisions based on new knowledge is a sign of intelligence and indicates a growth mindset. Lastly, all models fail at some point so it is equally important to help students recognize what concepts and ideas are represented well in their analogy as well as the limitations.

SUPPORTING MATERIALS

- S1. Construction of Analogies – Items with Suggested Answers
- S2. Construction of Analogies – Reflection Sheet
- S3. Construction of Analogies – Exam Questions
- S4. Construction of Analogies – Instructor Rubric
- S5. Construction of Analogies – Group Worksheet

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Table 1. Alignment of learning objectives with evidence.

Learning Objective	Evidence for Meeting Learning Objective
Create a model that incorporates multiple components of biological information systems, based on a familiar instructional item.	Product of the activity is a written model and/or oral presentation. Students should be able to identify the majority of analogous facets of the household object using the activity prompts.
Build an extended analogy from the starting model that differentiates between different levels of organization of genetic information.	Product of the activity is a written model and/or oral presentation. The facets of the household object identified should relate to each other cohesively, in the same way as different levels of genetic information.
Critique an analogy that describes the relationship of DNA with information flow, exchange and storage.	Students are asked to critique another group's model. Their reflections should show evidence that they can identify strengths and weaknesses in terms of accuracy and/or cohesiveness.

Table 2. Lesson timeline. The lesson can be completed in one session or two, depending on the length of the class, the number of groups, and the instructor's preference.

Activity	Description	Estimated Time	Notes
Preparation for Class			
Select items for class	You will need an item for each team of students. Decide how many you need and whether they will be physical items, photos/descriptions of the items, or a mixture. Prepare one item per team. See Supporting File S1.	Variable: at least 10 minutes	If you want to use physical items, you will need to take some time to identify, collect and label them. If not, you can just print out photos/descriptions.
Print group and individual worksheets	Print out one copy per team of the group activity and one reflection sheet per student.	10 minutes	See Supporting Files S2 and S5.
In Class			
Introduce the lesson	Tell students that you will be working on a group activity where they will be developing an analogy. Ensure they know what an analogy is by giving a simple example that does not have to do with information (*e.g.,* blood vessels are like roads).	2 minutes	Students should sit in groups of 3–4 for this activity. They can work with whoever is near them or in groups that you form.
Hand out items and worksheets	Give one item and one worksheet to each team. Let them know that they will have to present their model to the class.	5 minutes	You can hand them out at random or let groups choose.
Group work	Have students answer the questions on the worksheet with relation to their particular item. Circulate during the discussions to provide encouragement and feedback. Ask probing questions to make sure they have their definitions right and that they have thought through their answers.	30–45 minutes	If students get stuck, you can give hints or suggest that maybe they need to rethink their starting point. If students say they are finished, encourage them to extend the analogy even further (*e.g.,* what is a restriction enzyme in this model? what would be a histone?) or ask them to come up with a new item for a future class.
Presentations	Pass out reflection sheets to all students. Call each group to the front of class to present their model. Give them a limited amount of time (we suggest 3 minutes) and ask them to describe the item as well as their reasoning.	10–30 minutes	Depending on how many teams and how much time you have, you can ask all teams to present in person at the end of class, or you can do it during the next class, and/or you can have selected teams present and the others turn in written presentations.
Individual reflections	Students are encouraged to pay attention to all other teams during the presentation and to critique or extend another team's work on the individual reflection sheet.	3 minutes	This part of the lesson could optionally be extended to require students to respond to more than one other team's work (or even all others). If so, more time might be needed between presentations.
Assessment			
Informal feedback	Ask clarifying questions and praise particularly creative ideas after each team presents. Collect worksheets and reflection sheets. Collate ideas from other students and your own critiques. Return feedback to teams.	10 minutes per team	You can spend as much or as little time as you want on providing feedback. It also depends on how much feedback you were able to give during class. Of course, the more you can engage with them, the more they will learn. We would recommend providing comments but not grading their answers for correctness. Be open to students providing different answers from the key, but look for cases where the logic is incorrect or the model breaks down. You can also post the provided answer key (Supporting File S2) to the entire class if you like.

Activity	Description	Estimated Time	Notes
Formal feedback (optional)	Give students time to revise their analogies using feedback from instructor and peers. Score final analogies using the provided rubric.	10 minutes per team	See Supporting File S4. Each item included in the analogy can be scored, and a final grade can be assigned based on the number of components included (*e.g.*, 10 components would be a maximum of 30 points, so total score would be divided by 30 to give a percentage). If desired, you can require a minimum number of components included in the final analogy.
Exam (optional)	Select one or more questions from the examples provided and copy into your exam.	2 minutes	See Supporting File S3.

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