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Exploring the Unknown

Fostering critical thinking in Earth and space science

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Ask your students a question that doesn't have a right or wrong answer, and what happens? Usually, silence. Not even your most eager pupils raise a hand. Why? Students are conditioned, especially in science, to come up with a definitive answer. Plug force and acceleration into Newton's second law, and you'll get mass. But what if you ask: "What will Earth's average temperature be in 2100?" No one equation will provide the answer.

Scientists get excited about what they don't know. They regard questions without answers as great unsolved mysteries. They look critically at data and evidence, make observations, formulate ideas, and ask new questions. Can we generate similar enthusiasm among students, encouraging them to think critically about the data and evidence and arrive at answers even when 100% certainty isn't possible?

This article describes The Concord Consortium's "High-Adventure Science" project. The project's goal is to bring frontier science into the classroom, allowing students to explore questions in Earth and space science that scientists are currently investigating. We don't expect students to solve the problems but rather to experience doing science like real scientists. What matters is the approach—based on thinking critically about evidence, making predictions, formulating explanations, and drawing and qualifying the certainty level of conclusions.

A new approach

The High-Adventure Science project offers three free online investigations (see "On the web") that focus on current, compelling, unanswered questions in Earth and space science and develop students' scientific reasoning and argumentation skills. The project provides tools that help students evaluate scientists' claims—and their own—while considering the level of certainty behind those claims. The investigations raise these questions:

- What will Earth's climate be in the future? (Students investigate past climate and predict future climate based on feedback mechanisms on global temperature.)
- Is there life in space? (Students learn how scientists use modern tools to locate planets around distant stars as they consider the probability of finding extraterrestrial life.)
- Will there be enough freshwater? (Students evaluate whether underground stores of water will support the world's growing human population.)

Each investigation includes interactive, computer-based models; real-world data; and a video of scientists working on the same unanswered questions. Students use the models, interpret the data, and draw conclusions—just as scientists would. The embedded tools that require students to think critically to explore evidence, make claims based on evidence, and discuss issues of certainty (i.e., the level of confidence, ranging from "not at all certain" to "very certain") make these investigations unique.

Fostering critical thinking

The online computational models and simulations cultivate critical thinking by allowing students to examine the behavior of complex systems that are otherwise difficult to understand (Feurzeig and Roberts 1999; Horwitz 1999; White and Frederiksen 1998, 2000). Students manipulate tools and models—trying different parameters, arrangements, and initial conditions—then run experiments and quickly see the results of their choices.

For example, in the five-day "Will there be enough freshwater?" investigation, students use a dynamic computer model and real data to study the water cycle and then evaluate the supply and demand for freshwater in various areas of the world. They explore the relationships between groundwater levels, sediment permeability, rainfall, and human impact on stream levels by changing properties and interpreting the results of their experiments (Figure 1). Students learn how water flows through sediments, how rates of recharge compare to rates of withdrawal, and how to assess the sustainability of water usage locally and globally. Finally, students consider their own water usage.

Uncertainty in science

Making and defending claims based on evidence are important to critical thinking, but our project also addresses the level of certainty about a claim. Our explanation-certainty item sets (Figure 2, p. 62) consist of four questions that require students to

1. make scientific claims (claim),
2. explain their claims based on evidence (explanation),
3. express their levels of certainty (certainty), and
4. describe their sources of certainty (certainty rationale).

Students don't naturally justify their claims or reason about their certainty (Kelly and Takao 2002; Sandoval 2003), but our item sets encourage them to do this, providing a way to measure critical thinking (Zohar and Nemet 2002). Building from scientific argumentation literature (Kuhn 2010; Duschl and Osborne 2002; Sampson and Clark 2008; Lawson 2003), we developed a construct that consists of six distinct levels. Higher levels indicate increasing proficiency; at these levels, students build more sophisticated scientific arguments (Figure 3, p. 62).

In the first activity of the water investigation, students encounter an explanation-certainty item set in which they analyze data to determine which is greater: direct or indirect use of water. Students estimate their own direct daily usage (e.g., showering, brushing teeth, drinking) compared to the amount needed to produce the food, clothing, and other

FIGURE 1

Sediment permeability and water movement.

This model shows a gaining stream cut into a moderately permeable layer (red) and a well that is placed near the stream. Students can change the location of the well and the rate of recharge to explore the relationship between sediment permeability and water movement.

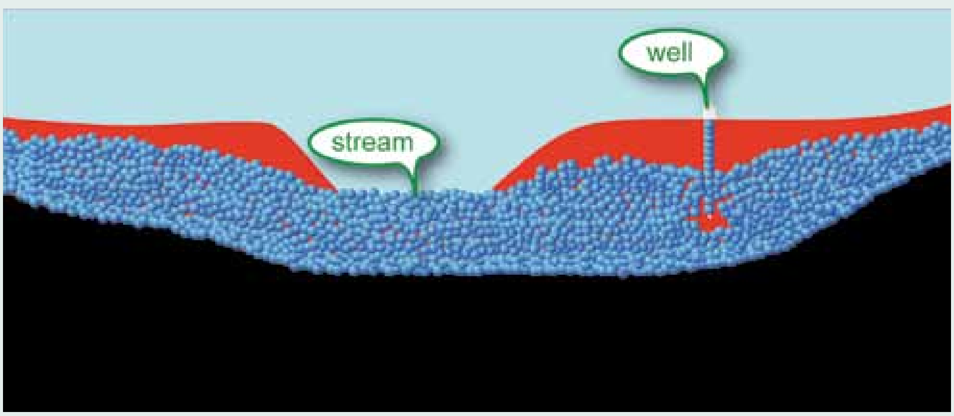


FIGURE 2

An example of an explanation-certainty item set.

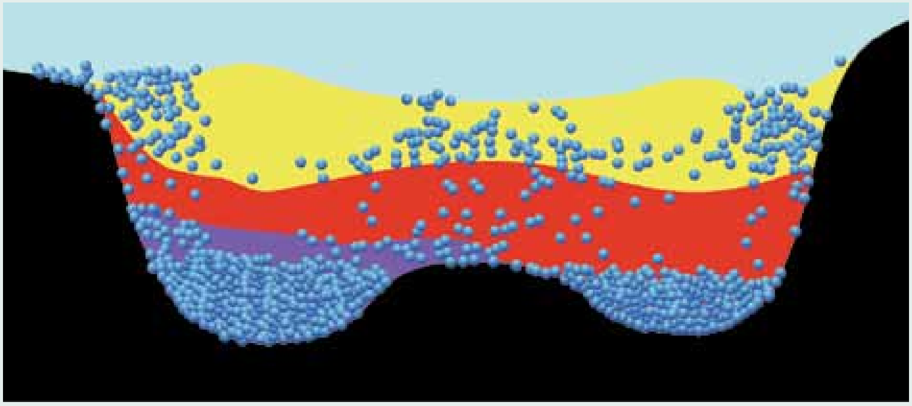
Claim: Identify and label locations that you think are likely to be good aquifers.

Explanation: Explain your prediction.

Certainty: How certain are you of your prediction?

1: Not at all certain
2: Somewhat uncertain
3: Neither certain nor uncertain
4: Somewhat certain
5: Very certain

Certainty rationale: Explain what influenced your certainty rating in the last question.



products they use each day. In calculating their total personal consumption, students can calculate how much water flows from the faucet during two minutes of teeth brushing, for example, or five minutes of showering. Students then estimate their indirect water usage, since indirect water use is not presented on a per day rate, arriving at various conclusions. The purpose is for them to reach a conclusion, rate their certainty, and explain what evidence influenced their certainty rating.

One ninth-grade student claimed indirect water use exceeds direct use: "The direct water usage averages 247 liters per day. As for indirect use, students may make a pot of coffee at breakfast, use sheets of paper for their work, eat slices of bread or apples for lunch, wear jeans all day, and have a hamburger for dinner. All these require water averaging way more than 247 liters."

This student expressed high certainty about her claim, choosing 4 on the 1–5 Likert scale (5 is "very certain"). Her rationale referred to data provided in the investigation: "The chart influenced my certainty because I could see that the indirect water use was larger." Certainty rationale items show whether students recognize the limitations of the evidence and whether they're relying too heavily on their own general knowledge or personal beliefs.

In the second activity of the water investigation, students use computational models to explore the geology and

FIGURE 3

Scientific argumentation construct.

Level	Description	Student characteristics
0	Nonscientific claim.	Students can't make scientific claims.
1	Scientific claim.	Students make scientific claims without support or evidence.
2	Scientific claim coordinated with evidence.	Students recognize that evidence is needed to support a claim.
3	Scientific claim coordinated with evidence according to scientific theory.	Students use theory or established knowledge to identify adequate evidence to support a claim.
4	Modified scientific claim coordinated with evidence according to scientific theory.	Students recognize the uncertainty of a claim by analyzing limitations related to measurements, current theory or model, and phenomena under investigation.
5	Modified conditional scientific claim coordinated with evidence according to scientific theory.	Students recognize conditions in which the current claim may not hold.

hydrology of aquifers. The explanation-certainty item set (Figure 2) includes an image of a model from the activity, in which each color represents a different layer of sediment (blue dots represent water). The sediments have various properties, including permeability.

The first question (claim) seems fairly straightforward. Students should be able to see where water has accumulated. However, before running the model and placing a well, students may be unsure whether the purple or red layer is more permeable. This affects their certainty about which layer would be a better aquifer. Students' previous experiments with the model and real-world experiences affect their certainty, as well. For example, some students may already know that getting groundwater to flow through clay is difficult.

A 10th-grade student annotated a picture of the model (Figure 4) and answered the explanation-certainty item set about aquifers. He explained: "It only has two layers of rock/sediment that water has to travel through, so it's the better choice for a well because water can be replenished quicker." He rated his certainty as 3 on the Likert scale, noting on the certainty rationale: "I think the place I chose is more permeable, but I made an educated guess."

The explanation-certainty item set design is used throughout the project, exposing students to increasingly complex questions. We encourage them to reflect on evidence (from both models and real-world data) and evaluate how certain they are about their own claims.

Assessment

The explanation-certainty questions posed in the High-Adventure Science investigations are a useful way to assess students' critical thinking. Teacher guides for each investigation include suggestions on how to use the range of student responses to evaluate their critical-thinking skills and prompt discussions.

Pre- and posttests for each investigation also include explanation-certainty item sets. Figure 5 (p. 64) shows a rubric for scoring the explanation portion of an item from the water investigation pre- and posttest. We also developed a rubric to score the certainty rationales (Figure 6, p. 65). It groups students' certainty rationales into four categories:

1. no answer;
2. personal reasons;
3. reasons based on data from the investigation; and
4. reasons based on information from the investigation plus additional sources of information.

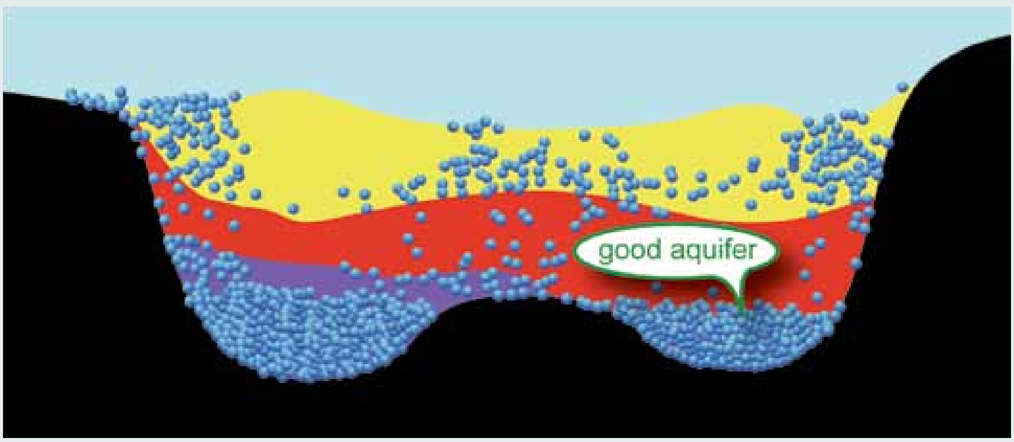
We analyzed the explanation-certainty item sets administered to 956 students by 12 middle and high school teachers in the northeastern United States. We concluded that students' justifications of claims and their certainty rationales reveal their degrees of critical thinking. We also note that students who can relate their claims to evidence are more likely to think about scientific factors when determining their levels of certainty.

Four hundred and nineteen students showed significant improvement in understanding of science content and scientific argumentation ability as measured from pre- and posttests for each investigation. Finally, we determined that students' posttest improvement in science content understanding and scientific argumentation skills was directly related to how well they performed on the explanation-certainty tasks within the investigations. In other words, the more students were exposed to the explanation-certainty item sets, the better they did on the posttest.

FIGURE 4

Student-annotated model.

In this model picture, the student identified the aquifer he thought was best for a well.



Conclusion

Scientists, and science in general, move from the unknown to increasing levels of certainty. Teaching students about science means encouraging them to embrace and investigate the unknown, make reliable scientific claims, justify those claims with evidence, and evaluate the quality of the evidence. In all areas of science—and especially in frontier science, in which claims can be disputed and changes arise with the discovery of new evidence—this level of critical thinking is key.

Schools often teach "known" science. By incorporating the unknown into the curriculum, schools can engage students in scientific ways of thinking. The High-Adventure Science project relies on the dynamic nature of frontier science to help students develop critical-thinking skills. ■

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FIGURE 5

Student explanation rubric.

Claim: A city receives water from local wells and discharges its treated wastewater into the ocean. Each of the city's residents uses 25,000 L of water each year. The city's annual precipitation is equal to 25,000 L per person. Is the city using its water supply in a sustainable manner?

Explanation: Explain your answer.

(**Note:** Students' explanations should include correctly cited data and the following ideas:

- Not all water that falls as precipitation will become groundwater.
- Some precipitation can run off.
- Some precipitation can evaporate.
- It takes time for infiltrated water to reach groundwater.
- The layer above the aquifer may be impermeable.)

Points	Level	Criteria	Sample explanations
0	Irrelevant: Off-task	Student didn't write anything or wrote unrelated text.	None "Because I think so."
1	No link: Nonnormative ideas	Student elicited nonnormative ideas or restated the question.	"There is lots of water. The world is mostly water." "They do not have extra water."
2	Partial link: Normative ideas	Student elicited one or more ideas listed above.	"All precipitation water will not go to the wells. It may be soaked up in plants, puddles, and so on."
3	Full link: Single link between two normative ideas	Student used two ideas that are meaningfully connected.	"Even though the amount of water used appears to be equal to the amount of precipitation, not all the water from the precipitation is available. Some of the water evaporates."
4	Complex link: Two or more links among three or more normative ideas	Student used three or more normative ideas that are meaningfully connected.	"The precipitation equals use, however not all water will end up where it can be used. In a city, the land is covered by pavement. The pavement is impermeable, so water will run off and not soak into the ground."
Total points			__/4

FIGURE 6

Certainty rationale rubric.

Points	Category	Source	Description of categories
0	No information	No response	Didn't respond.
		Simple off-task responses	Wrote "I do not know" or similar answers. Provided off-task answers.
		Restatement	Restated the scientific claim or uncertainty rating.
1	Personal	Question	Did or didn't understand the question.
		General knowledge or ability	Did or didn't possess general knowledge or ability necessary in solving the question. Did or didn't learn the topic. Can or can't explain or estimate.
		Lack of specific knowledge or ability	Didn't know specific scientific knowledge.
		Difficulty with data	Didn't make sense of data provided in the item.
		Authority	Mentioned teacher, textbook, and other sources.
2	Scientific within investigation	Specific knowledge	Referred to and elaborated on a particular piece of scientific knowledge directly related to the item.
		Data	Referred to a particular piece of scientific data provided in the item.
3	Scientific beyond investigation	Data or investigation	Recognized the limitation of data in the item. Mentioned that not all factors are considered.
		Phenomenon	Elaborated why the scientific phenomenon addressed in the item is uncertain.
		Current science	Mentioned that current scientific knowledge or data collection tools are limited.
Total points			__/3

On the web

The Concord Consortium's High-Adventure Science project: *www.concord.org/projects/high-adventure-science*

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