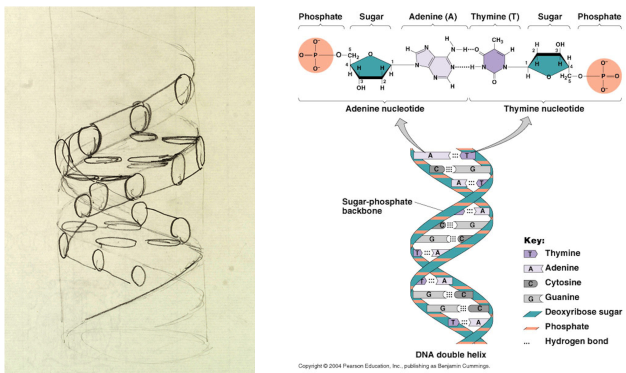
Models and Modeling: An Introduction

Modeling is the process by which scientists represent ideas about the natural world to each other, and then collaboratively make changes to these representations over time in response to new evidence and understandings. Models appear as drawings on whiteboards in laboratory hallways, as diagrams in research articles, and even as sketches on napkins. Wherever they appear, they are, or will be, an object that reflects changes in thinking about some set of ideas. Models don't just reflect reasoning, they also stimulate new ideas.



Original drawing of DNA by Francis Crick and conceptual model today

Modeling is intimately connected to several other *practices* that scientists engage in, all for the purposes of building knowledge—these include asking questions, designing studies, collecting and analyzing data, arguing about evidence, and communicating findings. In classrooms teachers also engage students in these practices, but modeling is unfamiliar as a practice to most educators and to students. In this paper we describe how modeling works in concert with all the other science practices in the classroom to promote students' reasoning and understanding of core science ideas.

Modeling usually works in tandem with another practice—explanation. These two practices are at the heart of disciplinary work. Explanation is a keystone activity because the ultimate aim of science is to describe why the natural world works the way it does. We refer to causal explanations here. Modeling is important because models are drawings or diagrams that represent one's current understandings about how a specific natural system behaves. In this way, models themselves can be a form of explanation (sometimes we can combine them as ideas by saying we are working on an "explanatory model"). In classroom settings, modeling and explanation are also unique among other practices, in that they don't just happen on a particular day. Rather, students' on-going attempts to revise major explanations and models are "stretched across" a whole unit of instruction.

From the past twenty years of research on learning, we know that children make dramatic advances in their understanding of science by generating and revising explanatory models. For both scientists and children, modeling is something done publicly and collaboratively; it organizes and guides many other forms of practice, and importantly it opens up opportunities to reason about ideas, data, arguments, and new questions.

We will later share with you two classroom examples of modeling in this reading. One is the story of a sophomore biology teacher who asked her students to consider an authentic puzzle facing wildlife biologists—Why in a forest ecosystem would a population of arctic hares rise and fall in regular seven-year cycles? Her students initially drew simple diagrams that linked the hares with available food sources and their main predators. As the unit progressed and students learned more, they returned to these diagrams and created new connections, erased others, and added explanatory depth to every aspect of their models. They used their models to ask new questions, to recognize gaps in their understandings, and considered what types of evidence they needed to generate in order to solve the complex puzzle of the up-and-down hare populations.

The second case of modeling is about a third grade class studying the physics of sound. This teacher also began her unit with a puzzling phenomenon to explain—how can a singer shatter a glass with just his voice? The young learners began with drawings that largely showed what was observable, which included the singer facing the glass, the glass vibrating and then breaking. But as students conducted their own experiments in the following days, and were introduced to ideas like "sound as waves," they began to add new explanatory features to their models, such as energy being produced by the singer's diaphragm, air molecules bumping up against one another as energy moves through space, and the idea of the glass resonating in response to the energy from the sound waves. These students revisited their models twice during the unit to add new features and to make their explanations more coherent.

In this chapter we explore a number of questions that teachers often ask about models, such as: "What counts as a model?", "Are the models that scientists use different from the ones I should be using with students?", "What does the process of modeling look like in the classroom?", and "How does modeling help my students learn?" We share more about the two classrooms in which the ecosystem and sound unit modeling unfolded. In the process we'll help you envision what this type of teaching could look like for your students.

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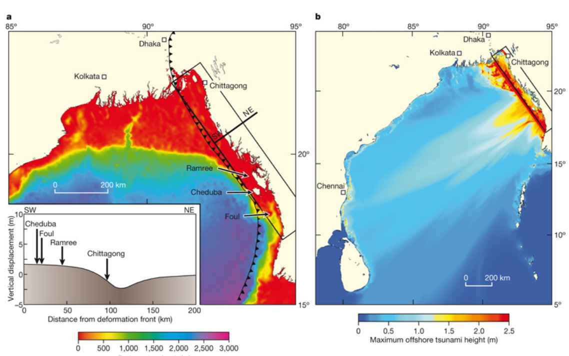
What are models?

A scientific model is a representation of a system (such as the human respiratory system, the solar system, a system of electrical circuits) or a phenomenon (such as the changing seasons, the oxidation of metal, or humans maintaining their body temperature). These representations can take the form of drawings, diagrams, flow charts, equations, graphs, computer simulations, or even physical replicas (such as a tabletop model of a watershed). In an upcoming section, we describe why *only a couple of these types of representations are appropriate* for modeling in a classroom.

Models usually include only features that are important to understand the system or phenomenon, and they leave extraneous information out. For example, in modeling a system of pulleys and weights, one might draw the pulleys, the strings or ropes, the weight, perhaps who was exerting a lifting force, and the forces themselves. What might be left out are the surface features of the object being lifted and the details of the person or thing doing the lifting. None of these would help us explain how the pulley worked, or help us predict whether the pulley could lift a particular weight.

Scientific models are made to be dynamic. Just as science knowledge changes with new discoveries, scientific models have to change too. Scientists often reconstruct models so that they can be useful in explaining a wider range of circumstances. In other words, an improved scientific model is usually consistent with both new and old scientific evidence. For example, the molecular model of DNA helps us explain some of the same patterns of inheritance that Mendelian models of genetics did, but also suggests why traits appear to be "switched on or off" in response to environmental conditions outside the organism. So models serve several important functions in science—they don't just "represent", they help groups of scientists *generate predictions*, *construct explanations*, *show gaps in knowledge*, and *pose new questions for investigation*. Models can be used to produce new understandings or to communicate understandings to others—and are often used for both purposes at the same time.



Tsunami model for 1762 earthquake in Bay of Bengal

Models and modeling in the classroom

Teachers frequently use models in the classroom, in fact textbooks are full of these representations. Unfortunately models are used very narrowly by most teachers; they are often employed simply to illustrate science ideas. They are used as props to show, point out, or provide examples of a system or phenomenon.

Even when teachers ask students to draw out their own understandings in the forms of pictures or diagrams, such displays are disconnected from knowledge-building activities—students simply "posterize" (create posters of) science ideas that can already be found in textbooks, like the water cycle or the steps in mitosis. One could say this is “using models.” But these experiences don't support learning very well, in part because they don’t require students to solve problems situated in everyday circumstances, to develop ideas or to make connections among ideas.

The more rigorous work that scientists and students can do is to *construct*, *test*, *evaluate*, and *revise* models. It is during these kinds of work that students see the need to learn new science ideas, to reason about how ideas and events are related, to argue about evidence, and to monitor their own thinking along the way. This is the work of modeling and these are the activities that build knowledge.

Five qualities of models make them useful for modeling in science classrooms. This means that not all types of models that we have mentioned are appropriate for engaging student in the process of modeling.

1) The first quality of “models for modeling” is that they should represent an event or process (we often use the term “phenomenon” for this), rather than “things.” For example, to engage students in understanding cells, teachers we have worked with have asked students to draw and refine models of the spread of cancer in human body tissues. Although students certainly need to know the names and functions of particular cell organelles, we do not ask them to re-create textbook representations of these parts, using plastic baggies and pipe cleaners. We focus them instead on how and why cell structures contribute to healthy functioning or to disease. To cite another example, the earth-moon-sun system is a thing. It is possible to create scale models of it’s parts—many students do—but this is not the kind of modeling that scientists do, nor does it engage students to do more than simply reproduce textbook ideas. In contrast, it is possible to use the earth-moon-sun system to identify an event or process that one could create a dynamic model of, then test and revise it over time. Such events might be captured in the questions “What causes the seasons?”, “Why are there no seasons if you live near the equator?”, “Why do planets and moons maintain the orbits they currently have?”, or “Why are solar eclipses so rare?”

2) The phenomenon should be context-rich, meaning that it is about a specific event that happens in a specific place and time under specific conditions. These “specifics” are precisely what make the models interesting to kids. Explaining how all these contextual features affect the event is also what makes the explanations much more rigorous (not copy-able from a textbook).

3) It helps if students’ models are pictorial, meaning that there is some visual resemblance between the representations on paper and the process or event being modeled. If you are modeling how levers work, then a drawing of levers, a fulcrum, a load and lifting effort are needed. If you are modeling the spread of disease through a population, then an illustration of groups of individuals—some infected, some not—would be helpful.

This means there are some forms of models that are not appropriate for classroom modeling; for example, computer simulations, graphs, equations, or physical replicas.

Although these *are* powerful tools to use during the modeling process, they *are not* the kinds of model forms that students can test, evaluate, and revise over time.

4) The fourth characteristic of models for classroom modeling is that the representations include both observable and unobservable features. By unobservable we mean that key parts are not available to our senses or directly detectable by measurement technologies (such as telescopes, dissolved oxygen meters, thermometers, or even pH paper). Features one might include in an explanatory model might be unobservable because they are inaccessible (i.e. the layers of the earth or hormonal reactions in the body), because they are too small (i.e. atomic structures, chemical reactions), because they happen on a vast scale (i.e. the blocking of the sun's light during an eclipse) over long periods of time (i.e. stellar life cycles, evolution, continental drift) or they are conceptual (i.e. selective pressure, sound waves, unbalanced forces).

Simply put, explanatory models in science use unobservable features, events, processes, and structures to explain what we can observe. This is what is meant by theory (the unobservable) helping to explain what we see (observations, or patterns in data). This relationship is a two-way street because what we observe with our senses or with instruments is used as evidence to create a theory, or an explanatory storyline about the unobservable.

5) The final quality of models for modeling is that they are revisable. Because models show how events, things, properties and ideas are related to one another, students need to test these relationships out. As a result of readings, activities, discussions, and experiments, students make changes to their models over time. The most successful versions of models we've used are drawings on poster paper that can be added to or that can have sticky-notes attached to as comments.

In upcoming sections, we talk further about what teachers actually have students do during modeling. But for now, we want to make clear that models for modeling in classrooms 1) are about phenomena (events or processes) rather than things, 2) are not generic but are specific to a place, time, and situation, 3) have pictorial characteristics, 4) include both observable and unobservable features, and 5) are made to be revisable.

What does scientific modeling look like in the classroom?

To help you visualize the modeling process, we'll use two authentic examples. Carolyn, a third grade teacher was teaching a unit on sound. Bethany, a high school teacher, was doing a sophomore-level class on ecosystems. Both teachers started by looking at their curriculum as well as at the *Next Generation Science Standards*. They both considered a phenomenon (event or process) that could anchor their units. When we say units, we refer to two to three weeks of instruction focusing on a related set of core science ideas.

Carolyn chose the situation of a singer breaking a glass with the sound energy from his voice. She thought that as students were developing an explanatory model for this phenomenon, they would have to wrestle with the ideas of sound as energy, air as a medium of transmission, the characteristics of sound waves at the unobservable level

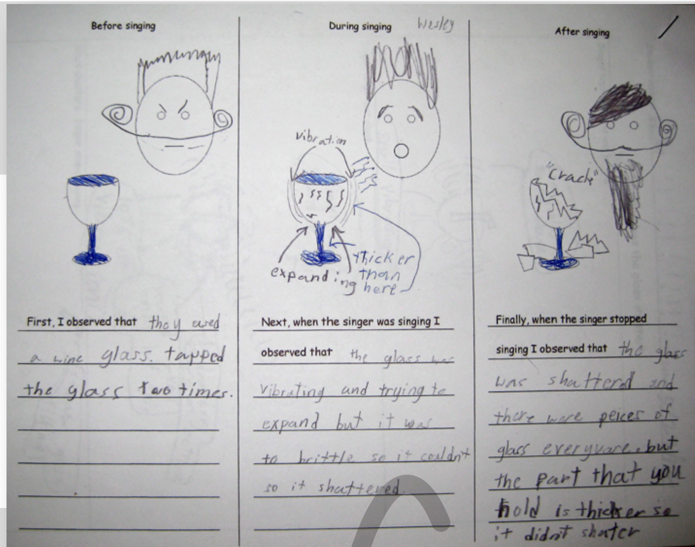
Third grade sound unit

Teacher planning:

- Prioritize the science ideas in the curriculum
- Select an anchoring event : Singer breaking glass
- Create model and explanation youself
- Line up activities and readings with what's needed in the final explanation

Day 1

- Elicit ideas about anchoring event
- Students hypothesize, draw initial models



Days 2 and 3

- Ideas: Sound as waves
- Activity: Soccer ball experiment

Days 4 and 5

- Ideas: How does force relate to volume?
- Activity: Tuning fork activity

Day 6

Student revise models and add to explanations: critique models of others based on new ideas, evidence

Days 7

- Ideas: Making, sensing sounds with the body
- Activity: Vocal cord and eardrum readings

Days 8 and 9

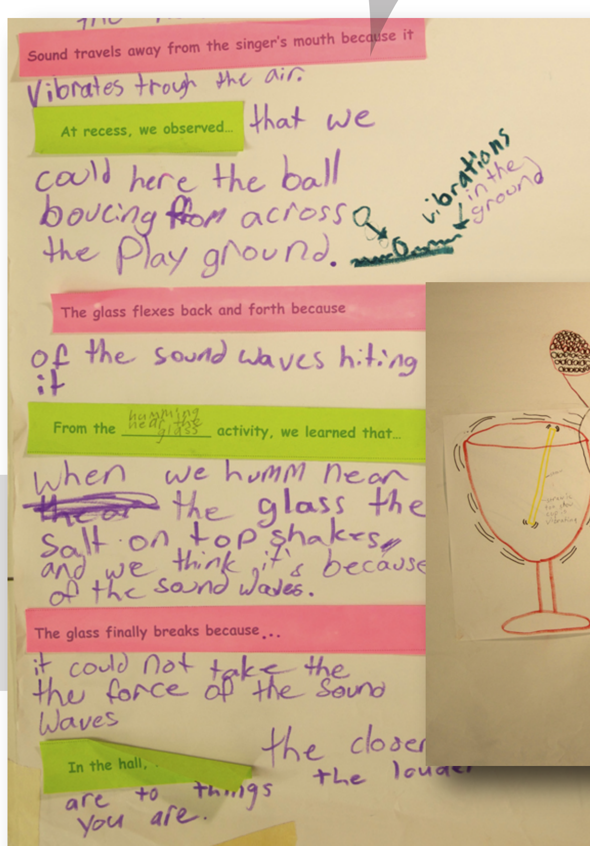
- Ideas: Sound traveling through media
- Activity: Obs. of sound in air, through solids

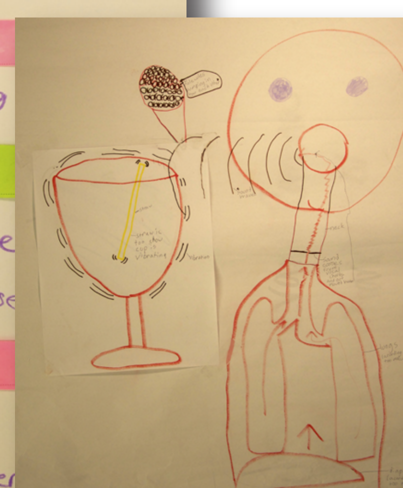
Days 10 and 11

- Ideas: Resonance and frequency
- Activity: Video and activity with humming

Day 12

- Preparing in small groups for final explanations, revising models, commenting on models of others





(wavelength, amplitude, frequency) and at the observable level (pitch, volume, the propagation of sound in all directions at once) and resonance. Her third graders would not only have to "know about" each of these ideas, but they would have to coordinate each of these ideas in an explanatory model for why the glass broke—in a particular way, at a particular moment, and under particular conditions. This is what we mean by selecting a phenomenon that is contextualized, and not generic. This is also what makes carefully designed units, based on modeling, far more rigorous than simply "covering curriculum."

To prepare for her unit, Carolyn and her teaching partner spent time beforehand constructed their own causal models and wrote out their own explanations for the glass shattering. During this process they found where the gaps were in their understanding and sought out resources to help them create more coherent and accurate models before the unit started. This pre-planning also helped them see what parts of their curriculum kits would be relevant to students' final explanations and which parts would be set aside.

In the high school example, Bethany engaged in the same planning processes with her colleagues. They decided to ask students a question that was simple to express but challenging to fully explain: Why in a local ecosystem was the population of hares oscillating up and down every seven years? After creating their own explanatory model, Bethany and her colleagues knew their students would have to coordinate the ideas of energy moving through an ecosystem in various forms, direct and indirect effects that populations of organisms have on each other, the concept of niches and competition for resources, and organisms' responses to changes in the environment.

We now present a basic overview of these units (see Figures 1 and 2), simply to show that modeling is not some exotic process that teacher might find unfamiliar, but rather it is linking the types of activity that most teachers already do (experimentation, readings, class discussions, etc.) in more purposeful ways, with the objective of supporting students to construct, test, evaluate, and refine explanations in the forms of models.

Carolyn started her unit with the video of the singer. Students were immediately intrigued and they offered observations without prompting: "He yelled right at the glass", "I saw the glass shaking", "Only the top of the glass broke!" After some conversation about what they could see and hear in the video, Carolyn shifted their attention to what they thought was going on that they could not directly observe. Following this discussion students drew their initial models using a before-during-after template supplied by the teacher. Later that afternoon, Carolyn examined their drawings and noted both what students seemed to know already (partial understandings) and what their gaps they had in their thinking. She created a public document for class the next day that named the three or four predominant theories students expressed in their models, and had students comment on each.

Following the first day of the unit Carolyn engaged students in a series of lessons, some involving combinations of: introducing new ideas (such as air being made out of molecules), activities (using tuning forks to understand what frequency means), discussions (about why they think sound is energy), and debates (about whether sound travels equally fast in all directions from the source). Much of Carolyn's standard curriculum was used, but some lesson were re-arranged, some were re-purposed, and some thrown out entirely because they contributed little to the final explanation. All these decisions were based on two considerations:1) What ideas and experiences were necessary for the final explanatory models, and 2) What were students thinking currently?

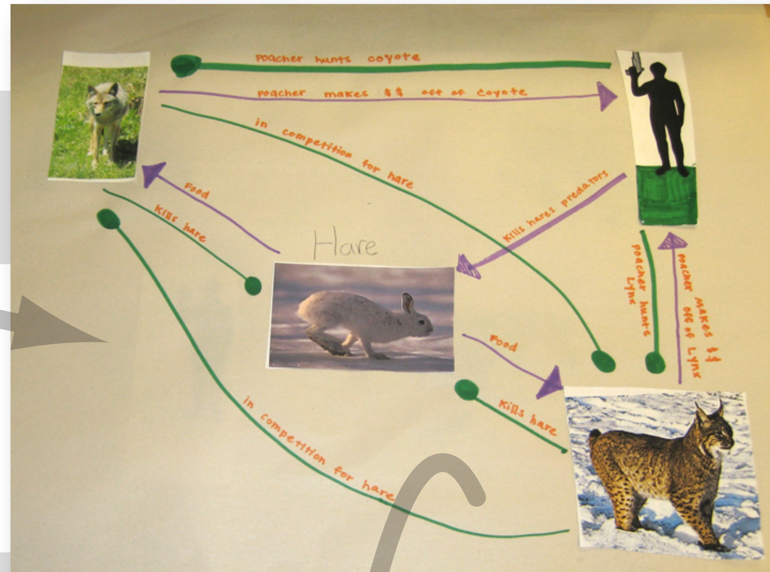
One episode on the third day of the unit demonstrates how students' curiosity about sound from their everyday experience compelled the teacher to do an unplanned experiment with them. On this day students came in from recess and reported that when they bounced a soccer ball on the pavement, people in different places around the playground could hear it. Some students developed the hypothesis that sound might travel in all directions from the source. Other students said that if this was true, it would be different from what they drew in their initial models, where they portrayed sound as moving from the singer's mouth in a straight line towards the glass. The teacher asked them to consider what a fair test might be of the hypothesis that sound travels in all directions from the source. Students decided to go back out to the playground, arrange themselves in a large circle about sixty feet in diameter and then bounced the soccer ball. They each signaled when they heard the bounce.

Returning to the classroom the teacher asked them to draw out their soccer ball sound data. Students found out that, indeed the sound appeared to be traveling outward in all directions at once and with equal speed. Some students claimed that sound waves might be like waves from a pebble thrown into a pond. Carolyn asked "Why do you think that?" and "What might this tell us about the singer breaking the glass?" The students were then given a chance to evaluate their initial models and revise them if they desired. Carolyn prompted them by asking, "Based on what we learned, what should we add? Revise? What still puzzles us?"

This two day period became one of five cycles of reading, discussion, and activity. In the "soccer ball" cycle alone, students engaged in questioning, creating hypotheses, designing an experiment, making sense of data, and revising their models (six of the science practices listed in the *Next Generation Science Standards*). Notice how many other science practices were "bundled" with the practices of modeling and explanation. All of these various scientific practices were important for their understanding of the concept of sound as energy in a deep and connected way. Near the end of the unit Carolyn prepared the students to construct final written explanations and provided them with sentence frames as a way to talk about evidence. Their accompanying models were richly annotated drawings, linking activities and readings and scientific language, but expressed in ways that made sense to them. The post-unit drawing in Figure 1 shows what looks like an ice cream cone in the air between the singer and the glass, but it is a blow up of that space, showing how sound energy is causing molecules to bump against one another, creating waves. This is an example of how modeling supports rigor in the classroom, and what happens when you ask students to make sense of the natural world in their own words.

Sophomore unit on ecosystems

Teacher planning:
- Unpack the science ideas in the curriculum
- Select an anchoring event or process
- Create model and explanation youself
- Line up activities and readings with what is needed in the final explanation



Day 1
- Eliciting ideas about anchoring event
- Students hypothesize, draw initial models

Days 2 and 3
- Ideas: Biotic and abiotic factors in ecosystem
- Activity: Carrying capacity game

Days 4 and 5
- Ideas: Trophic levels and energy flow
- Activity: Simulation of energy tranfers

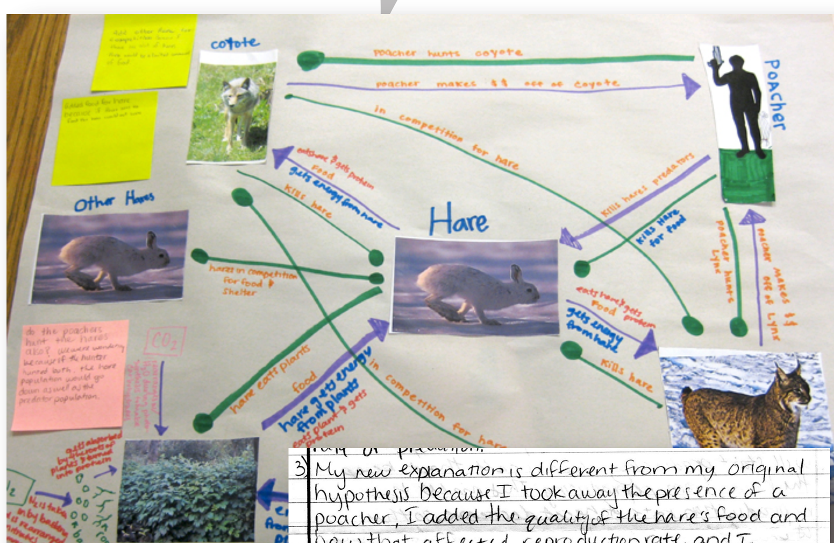
Day 6
Student revise models and add to explanations:
critique models of others based on new ideas, evidence

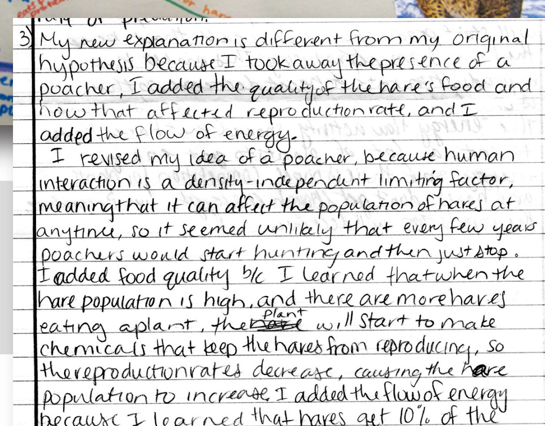
Days 7 and 8
- Ideas: Nutrient cycling in an ecosystem
- Activity: Readings on carbon and nitro cycles

Days 9 and 10
- Ideas: Food webs and predators
- Activity: Making food webs for arboreal forest

Days 11 and 12
- Ideas: Birthrates of hares and lynx, how plants respond to overgrazing
- Activity: Reading research data on plants under stress and effects on young hares

Day 13
- Preparing in small groups for final explanations, revising models, commenting on models of others




3) My new explanation is different from my original hypothesis because I took away the presence of a poacher, I added the quality of the hare's food and how that affected reproduction rate, and I added the flow of energy.
I revised my idea of a poacher, because human interaction is a density-independent limiting factor, meaning that it can affect the population of hares at anytime, so it seemed unlikely that every few years poachers would start hunting and then just stop. I added food quality b/c I learned that when the hare population is high, and there are more hares eating a plant, the plant will start to make chemicals that keep the hares from reproducing, so the reproduction rates decrease, causing the hare population to increase. I added the flow of energy because I learned that hares get 10% of the

In the case of Bethany, very similar patterns of teaching emerged. Bethany opened with the puzzle of why the hare population rose and fell with predictable regularity in seven year cycles. Her students drew initial models that were like concept maps, but still included pictorial representations of all the factors that they thought influenced the hare population. They also wrote out hypotheses to go along with their models. These hypotheses were just "trial balloons" for their later explanations, and included statements about the possible influence of climate change, new predators, the availability of plants for food, the birthrates of hares and lynx, poachers, and the role of wildfires. Because these separate hypotheses were made public, *students could then reason about the ideas of their peers*, and how these might be *resources for their own final explanations*. Students soon realized that the final models would integrate several of these hypotheses, and that scientists were not seeking "right answers" but rather models that could best predict and explain what would happen in ecosystems over time. Their written explanations at the end of the unit were, on average, two pages long and filled with connected, evidence-based assertions.

Bethany, like Carolyn, engaged in cycles of reading, activity, experimentation and the reconstruction of models. Each cycle allowed students to make their explanations more complete, to see where their gaps in understanding were, and to use the thinking of other students as resources to advance their own understanding. Bethany pressed her students to use scientific argument in their talk, asking them "What is the evidence for that part of your explanation?" "Why are you convinced by it?" "What alternative explanations are there?" Within a few weeks students were asking each other these same questions, without Bethany's prompting.

What's actually going on when modeling and explanation really works for students? As we can see from Carolyn's and Bethany's classrooms, productive examples of explanatory modeling share several characteristics:

- thinking is made visible and public with models,
- models serve to connect ideas arising from multiple activities and readings,
- teachers become more aware of student thinking and conceptual changes,
- models serve as concrete referents for students' hypothesizing and explanatory discourse, and
- models allow students to critique one another's claims and use of evidence.

It is now time to revisit why we say that "modeling and explanation are at the heart of scientific practice." Models represent students' current thinking. Because the model shows relationships, it also shows gaps in thinking. In this way the model serves as motivation to ask new questions and to propose new hypotheses. The experiments students do, then, are not arbitrary. *They have a clear purpose—not just to answer a textbook question, but to improve their own explanatory models*. This helps them decide what kind of evidence to collect and helps them argue for or against different parts of their current models with the evidence they now have. All these scientific practices, that are too often taught as isolated tasks, are now treated as an "ensemble" of meaningful activity.

Helpful advice from teachers who have successfully combined modeling and evidence-based explanations in their classrooms

Here are some principles that our teachers have used to guide their classroom practices around modeling and explanation.

- ***The unseen is vital in a model***: Always ask students to draw both observable and unobservable features. The exception here might be the initial models of early elementary students, where most of the features are accessible to observation or measurement.

- ***Show time passing***: Have students produce representations that show how the event or processes *change over time*, for example in "before-during-after" panels. Some of the most illuminating conversations among students involve what they think is going on before an event happens and why they think an event stops.

- ***How will we draw?***: Agreement about drawing conventions is important. After students have drawn an initial model, have a conversation with them about how the class should represent certain ideas, so that everyone understands each other's drawings (i.e. What do we all agree that arrows will mean? How will we agree to draw molecules? How will we show that time is passing?). Discussing how to show enlarged sections of a model is also very helpful (the prompt of drawing what you'd see if you had "microscope eyes" has worked very well for students).

- ***Provide simple templates***: For drawings that may be hard to sketch out, provide a template with outlines for students to use as a guide. When we ask students, for example, to draw out what they think is happening during homeostasis (such as regulating body temperature in humans), we provide an outline of a human body—that's all they need to get started. Their drawings are then a bit more comprehensible to the teacher and to peers in other groups.

- ***Keep track of activity***: Have student keep track of what they learn from each activity. In other papers we discuss how to keep a public record of all the activities that were done over the course of a unit and how these activities contributed to students' thinking about the final phenomenon. The public record can supplement what students might write in their own notebooks.

- ***Avoid model fatigue***: Have students change the model only once or twice in the middle of the unit, not every other day. They will get "model fatigue" if you go back to the drawings too often.

- ***Multi-modal communication***: Writing + drawing is really important. Many English Language Learners will be particularly helped by the drawing aspects of modeling, but everyone needs help in writing full explanations. Students also need assisted in writing about how evidence supports their explanatory models. Give kids "practice" time for this type of writing and consider scaffolds for these activities as well.

- ***Can't do it all***: The phenomenon *cannot* be the anchor for all the ideas one needs to teach in a unit of instruction, but it can tie together most of the major ideas. You will have to have some lessons that are not directly tied to the anchoring phenomenon in order to meet the demands of your curriculum and standards.

Conclusion: Teaching is about "Working on and with students' ideas"

In the classrooms we have described, the job of the teacher is to "work on and with students' ideas,"—not to march through curriculum. Working on students' ideas is about focusing on learning, whereas an exclusive focus on covering curriculum can ignore student learning. Modeling involves anchoring instruction in complex phenomena, making students' thinking visible throughout the learning process, supporting changes in these models in response to evidence and public reasoning, and developing causal explanations and arguments from these models. In the table below we contrast this type of teaching with more traditional forms of instruction.

	Working on student's ideas through modeling and explanation	Traditional forms of instruction
Purpose of instruction	Goal is for students to construct meaningful evidence-based explanations for a complex, puzzling phenomenon.	Goal is for students to reproduce generic models and explanations from textbooks or other sources.
Level of explanation for classroom activities	Students articulate "how and why" a phenomenon happened, using unobservable events and processes as the causes.	Students articulate "what happened" in detail, without necessarily using unobservable entities, processes or events to explain phenomenon.
Roles of activity and evidence	Models and overarching explanations are constantly and iteratively evaluated in light of new evidence from experiments, labs, or demos.	Experiments, labs, and demos provide "proof" that some scientific principle or fact is accurate. The conclusions are ends-in-themselves. Evidence is not talked about in terms of applicability to models or overarching explanations.
How student thinking is supported	Students' ideas made public through talk and drawing (models)—includes their hypotheses, partial understandings, puzzlements. Students give and receive feedback from each other on sets of ideas.	Student thinking is generally private. They are exposed to textbook ideas but are not asked to use them nor do they receive on-going feedback on their thinking.
Classroom talk	Students are asked to compare and contrast ideas, to evaluate models, to "reason out loud" and at length with one another.	Teacher talk dominates. Students are asked for and seek "right answers" to questions from the teacher.
Responsibility for learning	Instruction over the long term focuses on students becoming independent thinkers.	Students are dependent upon the teacher to tell them what they need to do next.

To sum up: The goal of modeling is *not* for students to produce a "correct answer" in the form of a drawing, nor is it to have students reproduce textbook explanations. The goals include students being able to represent science ideas, to ask questions about initial models, to learn to decide what types of information and data needs to be gathered to refine their models, to be able to add to or revise their models in response to evidence, to develop deep and well connected explanations from their models, to apply their "best version" of their models to new situations in order to predict and explain events and processes there. The understandings we want students to have are rich and gapless explanations of complex phenomena. To put it simply, the rigor of the instruction matches what children are capable of.

Acknowledgments for images used:

Original DNA drawing by Francis Crick, 1953.

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P. Cummins (2007). Models for the 1762 Arakan earthquake and tsunami: The potential for giant tsunamigenic earthquakes in the northern Bay of Bengal. *Nature* 449, 75-78.