

Creating Coherent Inquiry Projects to Support Student Cognition and Collaboration in Physics

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Douglas B. Clark, Arizona State University

S. Raj Chaudhury, Christopher Newport University

As a physics teacher, you have computer programs, labs, and engaging activities for your students. Individually, these excellent tools allow your students to investigate fascinating aspects of the physics curriculum. Integrating them into coherent inquiry projects, however, can dramatically increase their potential to support students' cognition and collaboration around core physics concepts.

The inquiry template presented in this chapter incorporates the four conversations outlined in Chapter 1, with an additional focus on engaging students in sharing and critiquing one another's reasoning as they collaboratively refine their understandings of physics phenomena. The template involves three phases: (1) students observe and reflect on phenomena and make predictions about underlying mechanisms, (2) students gather data to investigate these mechanisms as they build and refine their models, and (3) students discuss, critique, and refine these models within a larger group.

As discussed in Chapter 1, these phases occur in iterative cycles rather than a strictly linear sequence. These phases provide, however, a useful general trajectory for inquiry. Certainly, this template is not the only inquiry approach for physics. There are many valuable approaches depending on your pedagogical goals, but this one has the advantage of flexibly combining hands-on labs, simulations, discussions, and other activities into coherent inquiry projects across the curriculum.

In the following sections, the phases of the template will be discussed and illustrated with examples from a National Science Foundation–funded project called “Probing Your Surroundings.” Thermal equilibrium (or steady state temperature) is a challenging concept connected to many other core thermodynamics concepts, as well as several alternative conceptions grounded in students’ everyday experiences. Most scientists agree that all objects in a constant-temperature room should become the same temperature over time unless they produce their own heat (e.g., a lighted lightbulb or a living person). This happens because of a net heat transfer between higher temperature objects and lower temperature objects until all of the objects (including the air) are the same temperature.

Students, however, are aware from their daily experiences that some materials often feel hotter or colder than others in the room. Metal objects, for example, generally feel colder than wooden objects. The metal objects feel colder because they have a greater coefficient of thermal conductivity, which essentially means that heat transfers more quickly through them. As a result, heat transfers more quickly out of a person’s hand (which is a higher temperature) and into a metal chair than it does into a wooden table of the same temperature. Hence, even though the metal chair and wooden table are the same temperature as each other and the rest of the room, the metal chair feels colder because of its higher thermal conductivity.

Students often connect this experiential knowledge about how objects feel to their estimation of the temperature of those objects. Students may believe that metal objects are hotter or colder than wood objects in the same environment because that’s the way they feel. For example, metal objects in a warm oven feel hotter than other objects, so students assume that objects do not eventually reach the same temperature. To support this assumption, students often selectively revise other school-instructed thermodynamics ideas connected to thermal equilibrium, such as thermal conductivity. Students may assume that metals are hotter because they are better conductors and they “conduct in” more heat. In order for students to build robust understandings of science, they must make sense of core concepts like thermal equilibrium.

The Inquiry Template Phases

Phase One: Observing, Reflecting, and Making Predictions About Underlying Mechanisms

From a constructivist perspective, students learn by building on their existing ideas. As part of this process, students benefit significantly from reflecting on what they know about the phenomena under investigation and predicting possible mechanisms.

Engaging students' interest and providing bridges to their everyday experiences support cognitive engagement. You can begin the thermal equilibrium inquiry by reading the following excerpt from a home-improvement website: "Plastic bathtubs are better than metal bathtubs because plastic is not as naturally cold a material as metal, so the hot water in your bath should stay hotter longer than it did in the metal bathtub."

After this example, point out that people talk about objects being "naturally hot" or "naturally cold" and ask students to think about what they mean. As part of this process, prompt students to write their initial ideas in a journal. Most students assume that metal objects in the room are colder than the other objects. Students may provide reasons such as "the metal attracts cold" or "wool is warmer because wool warms things up." The goal of this phase is to engage your students in active reflection upon their prior ideas and experiences to provide a foundation to guide their subsequent investigations, as well as to facilitate their re-examination and revision of these initial ideas during the project.

After engaging students' interest, you should prompt your students to predict the outcome of a measurement or to hypothesize about the causal mechanisms driving the phenomena. A measurement contrary to students' predictions has the advantage of potentially creating a moment of cognitive dissonance you can use to promote focused thinking about the phenomena.

Students often focus on the surface aspects of phenomena rather than on the aspects that experts would consider critical. Students also have difficulty generating detailed explanations of phenomena. You should provide supports for students during the prediction process to help them focus on the salient issues and features. Hints, specific question prompts, and other scaffolding

can work wonders. Furthermore, these supports help students articulate their models in enough detail so that other students notice differences and want to discuss these differences in the third phase of the template.

Toward this goal, ask students to create an initial “principle” to explain the temperatures of the various objects in the room. Table 6.1 shows some phrases students can use to create their principles. You may provide these lists of phrases on a worksheet or use flashcards or other media. Students can use these phrases to create principles such as the following:

- When placed in the same room for 24 hours, all objects become the same temperature as the room unless they produce their own heat energy. These objects feel different because they transfer heat at different rates. (Note: Scientifically correct version.)
- When placed in the same room for 24 hours, objects that are good insulators stay at their original temperature regardless of the temperature of the room unless air can get inside them. These objects feel different because they are different temperatures. (Note: Materials with low thermal conductivity, such as wool and wood, often confuse students because such materials never feel as hot or cold as metal or glass in the same environment. Students assume that these “insulators” don’t change temperature.)

Where possible, physics inquiry projects should be situated within a real-world context with potential for connection to students’ interests. For instance, high school students about to get their driver’s licenses generally find a lesson on the role of air bags in car crashes to be practical and motivating. You will be helping them understand one-dimensional acceleration (and deceleration). Have students focus on the salient issues and levels of abstraction during their construction of their predicted model. You might also consider explicit instruction or discussion about the role of causal mechanisms in scientific inquiry to help students understand the goals of the lesson as well as the nature of science.

Phase Two: Gathering Data to Investigate the Mechanisms and Build and Refine a Model

Although *gedanken experiments* (thought experiments) play a critical role in physics when laboratory measurements cannot keep pace with theoretical

TABLE 6.1. OPENING SENTENCE PROMPT AND SUGGESTED PHRASES STUDENTS CAN USE TO BUILD THEIR EXPLANATORY PRINCIPLES

Choose one phrase from each column below to complete the following statement and build an explanatory principle: When placed in the same room for 24 hours...			
1. What kinds of objects?	2. What happens to the objects?	3. Qualifiers or conditions?	4. How do the objects feel and why?
<ul style="list-style-type: none"> • All objects • Some objects • Hot objects • Metal and glass objects • Wood objects • Cold objects • Objects that are good conductors • Objects that are good insulators 	<ul style="list-style-type: none"> • stay at their original temperature regardless of the temperature of the room • become the same temperature as each other but not the room • become close to but not exactly the same temperature as each other • become the same temperature as the room • become close to but not exactly the same temperature as the room • are at a different temperature than other objects in the same room 	<ul style="list-style-type: none"> • even if they produce their own heat energy. • unless they produce their own heat energy. • because they are made of different materials. • unless air can get inside them. • but only on their surface, not inside them. 	<ul style="list-style-type: none"> • The objects feel the same as each other because they are the same temperature. • The objects feel different because they are different temperatures. • The objects feel different because they transfer heat at different rates. • The objects feel different because they transfer heat at the same rate. • The objects feel the same because they transfer heat at the same rate.

advances, physics teachers have powerful tools and simulations to support their students' investigations. Donovan and Bransford (2005), however, raise a cautionary note in *How Students Learn: Science in the Classroom*:

Even when science instruction is shifted in the direction of engaging in scientific inquiry (as is happening more frequently in today's

classrooms), it can be easy to emphasize giving students “recipes for experiments.” ... These lockstep approaches shortchange observation, imagination and reasoning. (pp. 403–405)

You should focus and organize data gathering to help students build initial models to support their predictions and later refine those models in the face of further evidence or peer critique.

The inquiry goals are the same whether you use traditional laboratory equipment (e.g., thermometers, beakers, stopwatches, and other standard labware), computer-based probeware or micro-computer-based probeware (CBLs or MBLs), or computational models (simulations), but you should carefully consider the different data-gathering logistics for each of these approaches. Each approach has strengths and weaknesses in terms of your overall inquiry goals for integrating data gathering with model building and investigation (Bell 2005; Millar 2004). Traditional labware offers the benefit that students are often familiar with consumer versions of certain objects (e.g., thermometers). At the same time, labware requires careful training to ensure data quality (e.g., gauging the meniscus level on a column of water in a graduated cylinder). On the other hand, the use of computer-based probeware reduces the data-recording burden and facilitates multiple trials, which encourages further experimentation, a necessary step that allows students to revisit their initial experimental parameters in the process of building and refining their models.

Often, however, the phenomena under investigation will involve sizes or time-scales too small or too large to measure in the laboratory. Students cannot, for example, measure the average kinetic energy of gas molecules in a heated container at the molecular level with the labware and probeware typically available in secondary classrooms. Simulations (computational models) provide an invaluable addition to your tool chest in this regard. Simulations also have the advantage of allowing investigation of systems that would pose safety hazards in the classroom (e.g., radioactive decay or boiling water). Students working in pairs at a computer can collaboratively run simulations using initial parameters, observe the outcomes, record those outcomes, change variables in the simulation, record the new outcomes, and refine their models. You may need to help students connect their models and real-world observations. Students encounter difficulties investigating thermodynamics, for example, because “we neither see nor measure heat transfer *directly*. The quantities that we observe are masses and temperature changes, and we *infer* the amount of heat transferred from these observations” (Aarons 1990, p. 20).

In the second phase of the thermal equilibrium inquiry, students collect real-time data about the temperatures of objects found inside the classroom and explore interactive simulations dealing with such ideas as heat transfer, thermal conductivity, and thermal sensation. As students work through the activities, they record the data they gather and describe their observations. Together, these activities provide students with the empirical data and other scientific ideas needed to stimulate productive argumentation during the third phase.

You may give students thermometers, temperature strips (available at pet stores), or probeware (or a combination of the three) with which to make their measurements. Sometimes pedagogy dictates the most appropriate choice, as illustrated in the following vignette:

Mr. Caton's physical science students had completed their predictions and were ready to take measurements to test them. Mr. Caton knew that his middle school students often interpreted differences as small as a few tenths of a degree (e.g., between his lunch apple sitting on his desk and a metal chair leg) to mean that all objects did not eventually reach thermal equilibrium. So he decided to issue "low-tech" temperature strips (with a sensitivity of about one degree) as opposed to ultra-sensitive electronic probes, which measure one-tenth of a degree variations. Two days later, Mr. Caton presented a whole-class demonstration, in which he melted chocolate chips at the end of a long metal rod. Mr. Caton decided that the rapid rate of heat conduction in the metal rod called for the speed and precision of probeware. As the demonstration ran, students could observe the visual (and aromatic) chocolate melting process and the real-time graphing display from the temperature probe simultaneously. Not only could Mr. Caton discuss the connections between his demonstration and a similar computer simulation from the students' project, but he could initiate discussions about precision in terms of the temperature strips and the probeware.

Cognitive science research indicates that people learn best when actively engaged in knowledge-centered, learner-centered, assessment-centered activities (Bransford, Brown, and Cocking 2000). These three attributes don't neces-

sarily spontaneously accompany one another. Knowledge-centered activities, for example, don't ensure learner-centered activities. Mr. Caton could have achieved a knowledge-centered approach by simply providing his students with a table of thermal conductivity coefficients and a worksheet to compare heat conduction in iron and wood. Mr. Caton's inquiry approach, however, made the activity more learner-centered by allowing students to discover the differences for themselves and asking further questions like, "Do all metals conduct heat at the same rate?"

This knowledge-centered *and* learner-centered approach allows students to engage with some of *their* questions as opposed to strictly following the teacher's directions. Finally, Mr. Caton provided students with formative and summative feedback that focused not only on the facts but also on the core ideas, connections, and processes of the project so that his assessments appropriately reflected, aligned with, and supported the rest of the activities within the curriculum.

Phase Three: Critiquing and Arguing Models Within a Larger Group

During the third phase, students examine different perspectives with the purpose of reaching agreement on acceptable claims or courses of action. The goal should focus on solving problems to advance knowledge rather than "winning" or "losing." Your students should use each others' ideas to negotiate and construct a shared understanding of the phenomenon under investigation in light of past experiences and new information.

To complete the third phase of the example thermal equilibrium inquiry, sort students into groups based on the revised principle they created during the second phase. The discussion groups should include students who have created different models so they can discuss multiple perspectives (i.e., their individual models). The members of a discussion group may enter an online threaded discussion forum or a face-to-face discussion with their principles included as the starting comments. Incorporating your students' own principles as the initial comments increases the social relevance and interest of the activity. The sorting process can be conducted by you, by software, or potentially by the students themselves (e.g., "Find three students who created different principles than you did.").

Figures 6.1–6.3 show transcripts of online discussions in a standard threaded discussion forum format (i.e., with the comments indented and placed beneath the parent comments to which they reply). The discussion segments (from data

gathered in the Probing Your Surroundings project) include the original spelling and syntax from the actual discussions. Each discussion segment involves a different discussion group with different students. Students often require significant support to achieve high quality interactions, but these segments demonstrate the positive potential of student discussions in this phase.

In Figure 6.1, for example, three student pairs focus their attention on challenging the grounds of one another's claims. The students are not the only people who have an active role to play. You might encourage the students in this example to think about differences between closed systems and systems that have sinks and sources.

Whereas the students in the discussion in Figure 6.1 focused on the grounds of the comments, the students in the discussion in Figure 6.2 focused their challenges on interpretations of the phenomenon.

Finally, in the discussion segment in Figure 6.3, Pair A questions the experimental methods used by Pair B to gather evidence. Their query reflects a value judgment about what should count as valid data and what methods can satisfactorily generate such data. These types of questions are essential in the process of knowledge co-construction.

The students also raise an interesting question about Styrofoam. Styrofoam is well-known as an excellent insulator—both hot and cold drinks maintain their temperature longer when placed in cups made of this material. However, as both Pair A and B noted, there is nothing special about the temperature of the Styrofoam cup. The students' own questions, therefore, open up the door for connections to other portions of the physics curriculum.

All of these issues provide you with excellent opportunities to extend students' inquiry as a facilitator and coach during the discussion and after. As part of this process, you should have the students reflect back to the original problem and make final revisions to their model at the end of the third phase of inquiry. After students complete their final revisions, you should engage them in a larger discussion. In the thermal equilibrium inquiry example, you might have the students feel a metal chair leg and a wood desktop and then ask them, "Are the leg and the desktop the same temperature?" The ensuing discussion will give you an opportunity to help students reflect on their conceptual starting point and evaluate what they have learned.

You can use any generic online threaded forum for these discussions. Simply have the students "paste" or type their refined principles from the second phase

FIGURE 6.1. ONLINE DISCUSSION SEGMENT 1*

Pair A (*initial statement made by a student pair*)

Sometimes some objects in the same surroundings at room temperature become within a few degrees of the same temperature unless an object produces its own heat energy. At this point, the objects are within a few degrees even though they may feel different.

Pair B (*response to Pair A*)

grant a computer produces heat energy, and when you checked its temperature it was about the same as the others.

Pair A (*response to Pair B*)

A computer does produce heat energy, but that does not mean that the heat energy will travel into the outside plastic casing. Also computers do not produce enough heat energy to make a notable change. A computer has a fan inside it for the purpose of cooling it down, so it will cool down the computer and when you test the temperature it will not be higher than its surroundings.

Pair B (*response to Pair A*)

Mr. Jones said that it did.

Pair C (*response to Pair B*)

I think that you are a little off on your information. I don't think the chair and computers are the same temperature. It is obvious from my experiment with Brian that the chair leg was definitely cooler than the computer because the chair leg is metal and it produces its own heat energy and the keyboard gets warmed from the warmth of the electricity and my hand.

Pair A (*response to Pair C*)

Metal does not produce its own heat energy. If it did it would be different from room temperature. From my experiment, the metal chair leg was 23.2°C, which was almost exactly the room temperature. However, the comp might be warmer because it produces heat energy.

*Original spelling and syntax have been maintained.

FIGURE 6.2. ONLINE DISCUSSION SEGMENT 2*

Pair A (*initial statement made by a student pair*)

In some situations all objects in the same surround at room temperature become within a few degrees of the same temperature even if an object produces its own heat energy. At this point, the objects are the same temperature even though they may feel different.

Pair B (*response to Pair A*)

If an object produces its own heat energy then it would not be the same temperature as other objects that dont produce heat energy. For example, when a light bulb is on it produces heat energy and is much hotter than other objects in the same surroundings. How do you explain this??????

Pair C (*response to Pair B*)

I agree with you, [Pair A], you are wrong!!!!

Pair D (*response to Pair C*)

I disagree with you. I agree with [Pair A].

Pair C (*response to Pair D*)

An object that produces heat will stay hotter than an object that does not produce heat. Like A LIGHT BULB, if it is on in a room it will be hotter than a table in the same room.

*Original spelling and syntax have been maintained.

into the discussions as their starting comments. Online threaded discussion forums provide an optimal context for the ensuing discussions because (a) students have time to reflect on and revise their contributions before they submit them, and (b) these forums allow everyone to participate simultaneously rather than forcing students to compete with one another for a chance to speak. These forums can potentially facilitate more equitable participation than generally occurs in face-to-face settings.

If you do not have access to online discussion forums, discussions can be conducted in face-to-face groups. In this case, you might choose to have students use white boards or large pieces of paper to record or diagram the critiques of

FIGURE 6.3. ONLINE DISCUSSION SEGMENT 3*

Pair A (*initial statement made by a student pair*)

In some situations some objects in the same surroundings at room temperature become within a few degrees of the same temperature, but this is only on the surface of the objects, not inside them. At this point, the objects are within a few degrees even though they may feel different.

Pair B (*response to Pair A*)

What about a styrofoam cup? I took the temperature on the inside, and on the outside and it was the same.

Pair A (*response to Pair B*)

How would you take the temperature of the inside? Did you break it open or did you just put the temperature probe inside of the cup?

Pair B (*response to Pair A*)

I actually pushed the end of the probe into the styrofoam cup.

*Original spelling and syntax have been maintained.

each principle. Students can then move between the principles as they consider the evidence from the activity and other experiences.

Although students have previous everyday experience with arguments, you should provide specific instructions and supports for students to focus on use of evidence to support or challenge claims. A class discussion about how scientific argumentation differs from everyday argumentation in terms of the goals and what counts as evidence may also prove valuable (see Chapter 8). The statement “I disagree because the lab showed that the temperatures were the same” is more appropriate than “I disagree because he’s wrong” or “I disagree because he’s stupid.” On a related note, students often accept presented information rather than question it. For this reason, you should guide students to question other students’ principles and identify weaknesses in their arguments. Choosing topics for which students have ample access to evidence supports this process.

Conclusion

As a physics teacher, you have an abundance of excellent resources to draw upon as you assemble your own projects. In traditional curricula, these re-

sources and activities remain relatively unconnected—perhaps the students make predictions and gather data for one lab, use computers as part of another project, and occasionally engage in debate for nature of science or socioscientific topics. Although these activities have value individually, the template described in this chapter flexibly combines these resources and activities into coherent inquiry projects across the physics curriculum and provides much richer learning experiences for your students.

The basic formula is simple. In this template, students first observe and reflect on phenomena and make predictions about underlying mechanisms. Students then gather data to investigate these mechanisms as they build and refine their models. Finally, students discuss, critique, and refine these models within a larger group.

For the overall formula to succeed, however, you must carefully structure and guide each phase. The examples in this chapter highlight some specific issues for your consideration. Often you can integrate your current activities, labs, and computer programs into the three phases of the template through this approach. With careful planning and orchestration, you can create powerful pedagogical synergies to support students' cognition and collaboration around core physics concepts across the curriculum.

