

## VISUALIZING CHEMISTRY WITH INFRARED IMAGING

*"If pupils were able to 'see' this phenomenon in terms of a transfer of energy from their body to the object, this sort of situation [that they believe metals are inherently colder] would likely be less of a problem than it seems to be at present."* — Professor Gaalen Erickson, University of British Columbia, in "Children's Ideas in Science," 1985, p.59

### INTRODUCTION

Many science concepts are difficult for students because they cannot be seen in the real world. Just as scientists are "prisoners caught in the framework of existing theories" as philosopher of science Karl Popper famously asserted, students, too, can be imprisoned by their own perception of the world.

To address one of the most notorious misconceptions in thermodynamics—that metals are naturally colder than wood—Professor Gaalen Erickson conjectured in 1985 that having students "see" the heat transfer from the body to the object might remedy the misconception (Erickson, 1985). What he needed was an infrared (IR) camera, which, at that time, was prohibitively expensive for educators.

Thirty years later, the technology has matured and the price of basic IR cameras has plummeted to \$200 or below. Professor Erickson's wish has come true. The simple IR experiment shown in Figure 1 represents an instructional design to test his hypothesis. This experiment provokes a cognitive conflict (Limon, 2001; Niaz, 1995; Rowell & Dawson, 1979; Waxer & Morton, 2012) between the visual and tactile inputs: Through an IR camera, students see that the metal bar actually appears to be warmer than the wood bar after the thumbs touch both for a minute (2nd row of Figure 1), while the sense of touch suggests otherwise. By lifting the thumbs and then immediately observing the residual heat in the metal and wood bars (3rd row), the difference in their thermal conductivities—a key concept to resolve this cognitive dissonance—becomes evident. A visual comparison of the temperatures of the thumbs (4th row) reveals that the one that touched the metal bar has lost more energy, which is why it feels colder.

This elegant example demonstrates the tremendous visualization power and teaching potential of IR imaging. In a sense, thermal vision opens a whole new world that has never been seen before to students. As a picture is worth a thousand words, real-time full-field IR imaging provides a visualization of an ongoing process that can be easily recognized. An IR camera makes generating such a visualization as simple as taking a photo with a common digital camera. What it can immediately show and tell would have taken students hours to get if they had to use thermometers to collect data and then connect the dots. By liberating students from laborious data collection, IR imaging can directly focus them on analyzing results. This acceleration can make laboratory learning more productive and increase the chance for students to explore more ramifications. These affordances make IR imaging an ideal tool for supporting guided inquiry, in which data analysis is typically viewed as more important than data collection in helping students develop thinking skills and conceptual understandings (Monteyne & Cracolice, 2004).

The applications of IR imaging in science are numerous as many physical, chemical, and biological processes that absorb or release heat can be visualized using an IR camera. In essence, *anything that leaves a trace of heat leaves a trace of itself under an IR camera*. The scientific implication goes far beyond the temperature

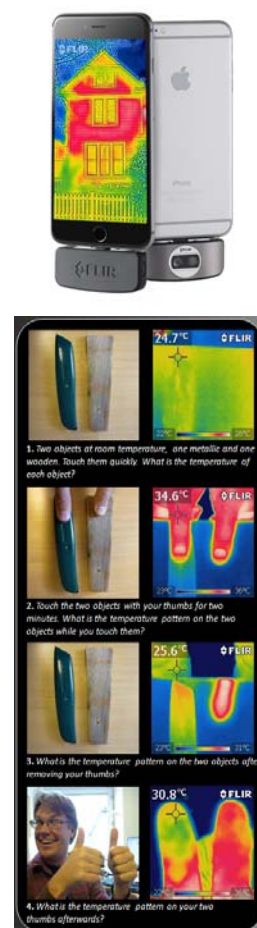


Figure 1. Upper: Low-cost IR cameras for smartphones. Lower: Four steps of an IR imaging experiment designed to provide a visual explanation of why metals feel colder than wood. This experiment takes only a couple of minutes to do and involves only a metal bar, a wood bar, two thumbs as heaters, and an IR camera. In the IR images, blue and white represent low and high temperatures, respectively.

distribution that an IR camera displays. Deep down, as required by the Law of Conservation of Energy, any change of thermal energy must result in or from the change of potential energy due to a physical or chemical process. Hence, from the change of the temperature pattern of a subject over time, one can infer what is going on behind the thermal scenes. The key ultimately lies at the microscopic level because thermal energy and IR radiation originate from atoms, molecules, photons, and their interactions.

Although IR imaging has broad applications across science, engineering, and medicine, this project will focus on exploring its potential for chemistry education. Chemists often rely on visually striking color changes shown by pH, redox, and other indicators to detect or track reactions. IR imaging represents a novel class of universal indicators that use false color heat maps to visualize chemical processes.

## GOALS AND OBJECTIVES

In response to IUSE's call "for proposals to design and study innovative learning opportunities," this Level I Development and Implementation project will design and study new inquiry-based learning opportunities in chemistry enabled by IR imaging. A team of chemists at Bowling Green State University (BGSU) and a team of learning scientists at the Concord Consortium (CC) will collaborate to carry out this interdisciplinary project. The goal of development is to create seven laboratory units based on IR imaging that can be integrated into general chemistry, physical chemistry, or biochemistry courses to support inquiry-based learning. The goal of research is to find evidence of learning due to IR imaging, identify the underlying cognitive mechanisms, and recommend effective strategies for using IR imaging in teaching. To ensure transferability to a large variety of audiences including two- and four-year colleges, the project will start with pilot tests at BGSU in the first year and scale up to include Boston College, Bradley University, Owens Community College, Parkland College, St. John Fisher College, and SUNY Geneseo in the second and third years. This project will accomplish these goals through the following objectives:

- **Design IR imaging experiments for a wide range of chemistry topics.** To demonstrate the versatility of IR imaging, these experiments will cover a wide range of topics, such as heat transfer, chemical reaction, phase change, colligative properties, enzyme kinetics, and light-matter interaction. Each experiment will guide students to discover a number of phenomena that can be clearly visualized with a low-cost IR camera (see Figure 2 for an example). Similar to differential thermal analysis (Brown, 2001), whenever possible, these experiments will provide a reference for the subject to compare (e.g., the pure ice in the right tray in Figure 2a/b). The design principle is to make the experiments as easy and safe to do as possible while leading students to more open-ended, deeper exploration. To ensure that these experiments will work under various laboratory conditions, we will recruit graduate students at BGSU to help test and improve each experiment thoroughly. In return,

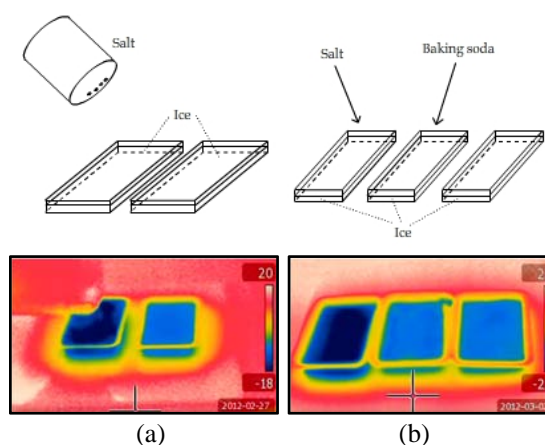


Figure 2. (a) IR imaging showed a significant temperature drop when salt ( $\text{NaCl}$ ) was sprinkled on ice, a phenomenon often simply explained as freezing point depression—a colligative property of solution. If students expect the left tray to warm up as a result of adding room-temperature salt to it, they would be surprised by the observation of cooling, which gives rise to a cognitive conflict. (b) Compared with salt, no substantial change of temperature was observed when baking soda ( $\text{NaHCO}_3$ ) was added to ice. This perplexing result, seemingly at odds with the simple explanation based on colligative properties, can spur students to search for an explanation and experiment further to test their hypotheses. For example, they can change the initial temperature of the ice to see if it makes a difference or test more substances such as sucrose ( $\text{C}_{12}\text{H}_{22}\text{O}_{11}$ ) to see if there is any trend. The quest for an answer will ultimately lead to complex molecular mechanisms that even sparked debate among chemists in *Scientific American* (Margrave, 2003).

they will gain valuable research and teaching experiences with IR imaging that will benefit their careers.

- **Develop laboratory units that integrate IR imaging experiments into chemistry courses.** The objective of these units is to help students integrate knowledge and deepen understanding as they try to explain macroscopic phenomena with microscopic concepts. To meet the diverse needs of the participating institutions, each unit will consist of a basic part and an extended part. The basic part will guide students to learn fundamental concepts through conducting simple experiments, whereas the extended part will support them to apply and/or integrate concepts in more complex experiments. For example, the basic part of a unit about colligative properties can be a visualization of freezing point depression (Figure 2a), whereas the extended part can be a generalization to other substances (Figure 2b). The basic part will take 30-60 minutes to complete, sufficiently flexible for instructors to adopt. The extended part will be more open-ended, paving a pathway to deeper learning. The development of these instructional units will follow the design principles formulated by *America's Lab Report* (National Research Council, 2005)<sup>1</sup>. To guide and teach scientific inquiry, all units will employ predict-observe-explain (POE) tasks (Champagne, Klopfer, & Anderson, 1980; White & Gunstone, 1992) as a scaffolding strategy to “bring thinking back to chemistry labs” (Mohrig, 2004). An objective of these POE tasks is to create and exploit cognitive conflicts between prediction and observation such that students are “forced to reconcile results, or confronted with a challenge to what is naïvely predictable” (Pickering, 1987). The units will use a causal diagram drawing tool to assist students to construct their own explanations and provide also formative assessment embedded in the POE tasks. In addition, we will develop a Laboratory Guide to assist instructors with implementing each unit and setting up the experiments (Figure 3). For instance, instructors should introduce the concepts of emissivity and reflectivity of substances and demonstrate their effects on IR imaging as prerequisites.
- **Conduct design-based research to transform IR imaging into an effective learning tool.** We plan a three-year design-based research study (The Design-Based Research Collective, 2003) with at least 1,000 students from seven institutions in four states. The research will use pre/post-tests and embedded assessment developed based on theories such as Knowledge in Pieces (diSessa, 1988, 2014) and techniques such as concept map assessment (McClure, Sonak, & Suen, 1999; Ruiz-Primo et al., 2004; Stoddart, Abrams, Gasper, & Canady, 2000) to gauge students’ conceptual development and knowledge integration through each unit. Of particular interest is the study of how IR imaging fosters the POE cycle through mechanisms such as **real-time full-field visualization**, **accelerated data collection**, and **cognitive conflict induction**, using indicators such as number of questions students ask, number of variables they change, and number of steps they iterate. Additional data sources include IR images, lab reports, student interviews, and video case studies from a subset of randomly selected students. The findings will inform the development work in each phase of the design-based research.
- **Collaborate with the participating institutions to test the laboratory units and scale up the research.** Instructors from six other institutions will join forces to implement the laboratory units and

*“Nothing tends so much to the advancement of knowledge as the application of a new instrument.”*

— Sir Humphry Davy



*Figure 3. Real-time imaging of an experiment (for testing light absorption) on a lab bench. As a non-contact tool, an IR camera can be used to freely observe an ongoing experiment from different angles and distances without disturbing it or affecting the result.*

<sup>1</sup> *America's Lab Report* proposed the concept of “integrated instructional units” as a strategy for connecting lab activities and other instruction. The report recommended four design principles: 1) Design with clear learning outcomes in mind; 2) Thoughtfully sequence lab activities into the flow of classroom science instruction; 3) Integrate learning of science content with learning of science practices; and 4) Incorporate ongoing student reflection and discussion.

educational research in their courses. To connect them, we will set up a public group on Facebook through which participants can post questions and share ideas. To support these collaboration activities, this project will provide each institution a small fund up to \$10,000. In addition, participants will convene at a one-day workshop prior to the implementation scheduled in Years 2 and 3 to review the laboratory units, brainstorm the instructional strategies, and go over the research plan.

- **Disseminate the project outcomes.** We will disseminate the laboratory units and research findings through presentations at conferences such as the *Biennial Conference on Chemical Education* and publications in journals such as the *Journal of Chemical Education*. The units will be freely available through a website dedicated to educational applications of scientific imaging.
- **Improve the outcomes through project evaluation.** An advisory board consisting of five experts from Beloit College, FLIR Systems, Harvard University, University of California Berkeley, and University of Miami will oversee and evaluate this project. Through routine communication and onsite meetings, the members will ensure that the project progresses as planned, the units are scientifically accurate and pedagogically sound, and the research is based on established theories and methodologies.

## RATIONALE

Learning by doing experiments is an indispensable part of undergraduate chemistry education (Reid & Shah, 2007). Unfortunately, many chemistry experiments comprise tedious cookbook-like procedures that are the likely culprit responsible for taking the fun part of science away from chemistry (Christiansen, Crawford, & Mangum, 2014; McComas, 2005; Mohrig, 2004; Monteyne & Cracolice, 2004; Sesen & Tarhan, 2013). This project will explore how low-cost IR cameras can be incorporated into chemistry laboratories as a powerful visualization technique to engage students and enhance learning in a constructivist way. A major advantage of IR cameras for industry applications is that technicians can use them to scan the subject, such as a power network or a building, to find anomalies rapidly. We expect that IR imaging, as a simple and high-throughput enthalpimetric analytic tool (Barin et al., 2015), can improve the efficiency and quality of inquiry-based chemistry learning in a similar way.

## Background Information about Infrared Cameras

An IR camera shows the temperature distribution of a subject based on detecting the invisible long wavelength IR radiation (8–15  $\mu\text{m}$ ) that it emits. A modern IR camera is an optoelectronic system made of thousands of microbolometers behind a lens that IR light can penetrate. It processes the electric signals from the microbolometer array roughly ten times per second and projects the pixmap onto a display screen to render a stream of images in which different colors represent different temperatures. Most cameras provide image analysis software for exporting spatial and temporal temperature data. Some new models can emboss the edges (lines at which color changes sharply) extracted from an image generated by a parallel digital camera onto an IR image to make the underlying structure recognizable. IR cameras have many applications in fields such as non-destructive testing, building diagnostics, electrical engineering, medical diagnosis (Diakides, Bronzino, & Peterson, 2012), and homeland security (Markoff, 2015).

Although IR cameras are not new, inexpensive lightweight models have become available only recently. The releases of two competitively priced IR cameras for smartphones in 2014 marked an epoch of personal thermal vision. In January 2014, FLIR Systems unveiled the \$349 FLIR ONE, the first camera that can be attached to an iPhone. Months later, a startup company Seek Thermal released a \$199 IR camera that has an even higher resolution and can be connected to most smartphones. The race was on to make better and cheaper cameras. In January 2015, FLIR announced the second-generation FLIR ONE camera, priced at \$249 (the first generation is now sold at \$129 on Amazon). With an educational discount, the price of an IR cameras is now comparable to what a single sensor may cost (e.g., Vernier sells an IR thermometer at \$179). All these new cameras can take IR images just like taking conventional photos and record IR videos just like recording conventional videos. The manufacturers also provide application programming interfaces for developers to blend thermal vision and computer vision in a smartphone to create interesting apps.



Not surprisingly, many educators, including ourselves, have realized the value of IR cameras for teaching topics such as thermal radiation and heat transfer (Cabello, Navarro-esbriâ, Llopis, & Torrella, 2006; Gfroerer, Phillips, & Rossi, 2015; Haglund et al., 2016; Möllmann & Vollmer, 2007; Schönborn, Haglund, & Xie, 2014; Vollmer & Möllmann, 2010; Xie & Hazzard, 2011) that are naturally supported by IR imaging. Applications in other fields such as chemistry, however, seem less obvious and remain underexplored, even though almost every chemistry reaction or phase transition absorbs or releases heat. In the following, we will explain with examples why IR imaging is an extraordinary tool for chemical education.

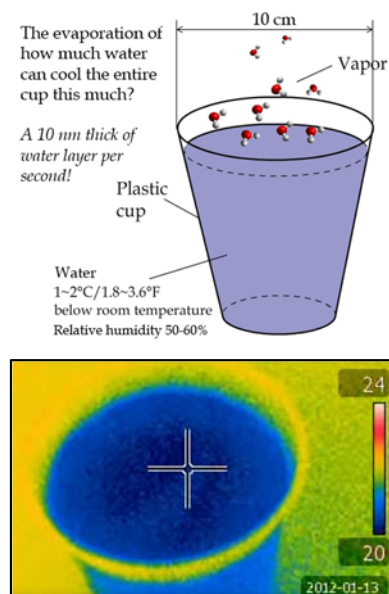
## Chemical Imaging Using Infrared Cameras

Scientific visualization is important in science education (Gilbert, 2005; Gordin & Pea, 1995). In chemistry, for example, molecular visualization is widely used to help students learn about 3D molecular structures (Craig, Michel, & Bateman, 2013; José & Williamson, 2005, 2008). Interactive visual simulations on the computer can provide virtual experiments that support inquiry-based learning (Honey & Hilton, 2011; Landriscina, 2013; Wieman, Adams, & Perkins, 2008; Xie & Lee, 2012; Xie & Tinker, 2006; Xie et al., 2011). However, not much has been done in exploring the educational value of scientific imaging for visualizing real-world phenomena and very little is known about how students learn from this kind of experience.

Scientists have long relied on powerful imaging techniques to see things invisible to the naked eye and thus advance science. If the price of an imager is not a barrier, scientific imaging can also become a visual learning tool that empowers curious students to see and probe further. A limited number of studies using remote atomic force microscopes (Jones, Andre, Superfine, & Taylor, 2003) and digital microscopes (Dickerson & Kubasko, 2007) have suggested that microscopy as a tool for seeing viruses and cells can have positive learning outcomes.

Chemical imaging is a technique for visualizing chemical composition and dynamics in time and space as actual events unfold (National Research Council, 2006). In this sense, IR thermal imaging is a chemical imaging technique as it shows temporal and spatial changes of temperature distribution from which we can then infer what is occurring at the molecular level. Most IR cameras are sensitive enough to pick up a temperature difference of 0.1 °C or less. In many cases, this level of sensitivity is sufficient to detect the thermal effect from a minuscule amount of reactants or a very slow reaction. Figure 4 presents a simple example that demonstrates this possibility.

This experiment, which concerns evaporation of water, cannot be simpler: Just pour some room-temperature water into a plastic cup, leave it for a few hours, and then aim an IR camera at it. In contrast to the thermal background, the whole cup remains 1-2 °C below the room temperature. About how much water evaporation is enough to keep the cup this cool? Let's do some calculations. Our measurement showed that, in a dry and warm room in the winter, a cup of water (10 cm diameter) loses approximately six grams of water over 24 hours, which translates into an evaporation rate of  $7 \times 10^{-5}$  g/s or  $7 \times 10^{-11}$  m<sup>3</sup>/s. Divided by the surface area of the cup mouth (0.00785 m<sup>2</sup>), we obtain that the thickness of the layer of water that evaporates in a second is only 9 nm—roughly the length of just 30 water molecules lining up! This nanoscale phenomenon cannot be seen by the naked eye, yet its thermal signature is so vivid under an IR camera. It is amazing



*Figure 4. IR imaging shows that the evaporation of water from a cup in a dry and warm room is able to cool the entire cup of water 1-2 °C below the room temperature. This persistent cooling effect is enhanced by the convective heat exchange that causes cooler water at the surface to sink and warmer water below the surface to rise. Continuous evaporation provides the driving force to sustain this effect. Covering the cup will stop this effect and settle the entire cup at the room temperature.*

that just the evaporation of this tiny amount of water at such a slow rate (a second to a molecule is like a geologic period to a human) suffices to keep the bulk of water 1-2 °C cooler than the ambient temperature.

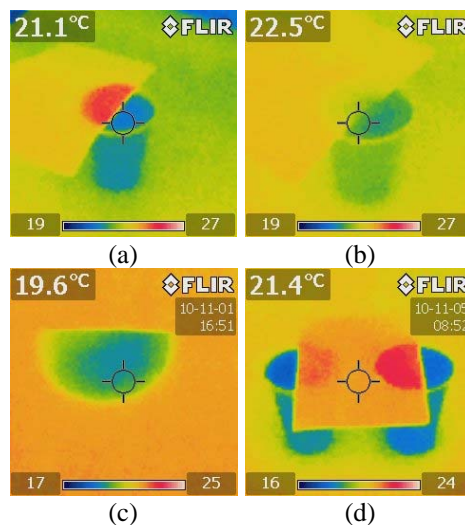
To delimit our work, this proposal makes a distinction between sensing and imaging by simply defining sensing as data acquisition using one or more sensors<sup>2</sup> and imaging as image construction using data obtained from a large array of sensors. Although the effect of evaporative cooling can also be investigated using a thermometer, students' perception may be quite different. Full-field imaging immediately reveals that the entire cup, not just the surface of water, is cooler. This holistic vision can bring many fleeting details, which would otherwise go unnoticed, to students' attention at once. As the devil is in the detail, trying to make sense of these details can prompt students to think more deeply, ask more questions, and explore further (as discussed in the next subsection). If we are to deliver the same kind of inquiry experience to students using a thermometer, more instructional support and time would likely be needed.

### Scientific Inquiry with Infrared Imaging

The above Fermi estimate of the evaporation rate actually raises more questions than it answers. Based on the latent heat of vaporization of water (2265 J/g), the rate of energy loss through evaporation should be only 0.16 J/s. This rate should have a negligible effect on about 200 g of water in the cup as the specific heat of water is 4.186 J/(g×°C). So where does the cooling effect actually come from? Would the temperature of water be even lower if there is less water in the cup to cool or if the cup is insulated to slow down its heat exchange with the environment? These questions can engage students in the core practice of scientific inquiry such as formulating hypotheses, testing them with experiments, and then asking even more questions.

The IR experiments shown in Figures 1-4 share a commonality: They are all easy and safe to do. None of them require expensive equipment, dangerous substances, or complicated procedures. Yet, they provide many opportunities for students to mull the results over and delve into deep science. The ease and safety of these experiments allow for wide adoption, potentially giving more students access to inquiry-based learning through conducting experiments (rather than watching demos). To further illustrate this point, let's look at the examples in Figure 5. These experiments involve only a few pieces of paper, a few cups of water, and some table salt. *But what a cup of water and a piece of paper can show is surprisingly plentiful and profound.*

**A violation of the Second Law of Thermodynamics?** Having observed a cup of water as shown in Figure 4, students know



*Figure 5. Chemistry on a piece of paper. (a) An IR image of a piece of paper half covering a cup of water shows the cooling effect due to evaporation at the water surface and the warming effect ( $>0.5$  °C) due to condensation on the underside of the paper (which is thin enough for heat to conduct quickly to the above side and show up in the IR image). The image was taken shortly after the paper was placed. (b) An IR image taken 15 minutes later shows that the paper settled at the ambient temperature, suggesting that the condensation onto the paper and the evaporation from the condensate on the paper have reached a dynamic equilibrium. The water looked slightly warmer because the evaporation area of the water in the cup was reduced by the paper cover. (c) An IR image of the paper taken immediately after it was removed from the top of the cup shows the evaporation of the water condensed to the paper earlier. (d) An IR image of the paper taken shortly after it was placed on top of a cup of saltwater (left) and a cup of freshwater (right) shows the effect of vapor pressure depression above saltwater.*

<sup>2</sup> Scientific inquiry in the material world is often supported by probeware that connects a sensor to a computer or a smartphone for displaying the collected data as graphs (Tinker, 2000; Vernier, n.d.). Typically, a sensor only measures a property at a single location. To see spatial patterns, students have to place a number of sensors at the same time or diligently move a sensor around while trying to keep the experimental condition as constant as possible.

that water in an open cup is slightly cooler in the steady state. We now ask them to predict what will happen if a piece of paper is put on top of the cup of water. Students may expect that the paper would cool as they have learned in the past that heat always goes from a hot place to a cold place. Through an IR camera, however, students see that the paper actually warms up (Figure 5a), seemingly against the Second Law of Thermodynamics. This cognitive conflict drives them to look for an explanation and do more experiments to test their hypotheses. For example, they can remove the paper from the cup and examine it under the IR camera to find evidence of water vapor deposition and condensation to the underside of the paper (Figure 5c): The observed cooling of the paper must be due to the evaporation of water that has condensed onto it earlier. But why does the condensation of water on the paper warm it up? This should lead students to the latent heats of evaporation and condensation. As evaporation takes away kinetic energy, condensation must return kinetic energy. The paper recovers that energy and warms up. This intricate thermodynamic cycle is illustrated in Figure 6.

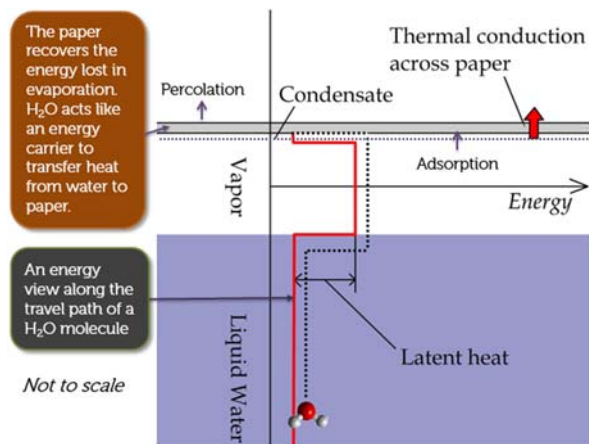


Figure 6. The warming of a piece of paper on top of cooler water is, in part, the result of a complicated process of energy transfer through two phase changes occurring at different locations: evaporation at the surface of liquid water and condensation on the underside of the paper. Neither process is visible to the naked eye but both can be observed through an IR camera. Adsorption also contributes to the warming effect.

**Heat of adsorption.** But is this the end of the inquiry? Absolutely not. If students do some calculations based on the heat of condensation of water (about the same as the heat of vaporization), they will realize that the condensation rate of just 9 nm of water layer per second (the condensation rate cannot be greater than the evaporation rate of water from the cup computed in the previous section) is not enough to immediately warm up the paper by more than 0.5 °C as observed. So where can the additional energy possibly come from? One source is the adsorption of water molecules on the surface of the paper: When a hydrogen bond is formed between  $\text{H}_2\text{O}$  and a cellulose molecule  $(\text{C}_6\text{H}_{10}\text{O}_5)_n$ , some intermolecular potential energy is converted into the kinetic energy of molecules (macroscopically this is called the enthalpy of adsorption). To prove this hypothesis, simply observe what happens after a drop of water is added to a piece of paper (or porous paper towel for a better visual effect). IR imaging shows that, as water spreads out on the paper, the moving edge of the wet area always appears to be warmer than the room temperature—in contrast to the inner area cooled by the evaporation of water. As there is no vapor condensation in this case, the warming at the moving edge—where cellulose and water molecules come into contact—can only be caused by the formation of hydrogen bonds. These IR visualizations of evaporation, condensation, and cellulose-water interaction may be used to correct a common misconception: Research based on the *Chemical Concept Inventory* (Mulford & Robinson, 2002) shows that 65% of students who finished general chemistry still believe that breaking bonds gives off energy (or making bonds takes in energy). Seeing IR visualizations opposite to their belief may trigger a cognitive conflict that leads to the remedy of this problem.

**Dynamic equilibrium.** The journey of inquiry continues as students leave the paper on the cup for 15 minutes or so and then come back to check it through an IR camera. They may be surprised (again) to see that the paper is now hardly visible in the IR view (Figure 5b), meaning that its temperature is almost identical to the room temperature. The explanation of this requires an understanding of dynamic equilibrium. The reason that the effect of condensation warming fades away is because water molecules can also evaporate from the condensate on the paper and take away energy. Initially, the amount of water molecules condensing onto the paper far exceeds that of water molecules evaporating from it. But after some time of vapor deposition and condensation, there are now enough water molecules leaving the paper. Eventually, a



dynamic balance between ongoing evaporation and condensation must be established. As there is no net condensation or evaporation, the paper temperature must be equal to the room temperature.

**Vapor pressure depression.** Now that students have discovered the effect of condensation warming, we can challenge them to exploit it to do something useful. For example, can the effect be used to measure vapor pressure? Ask students to add a few teaspoons of salt into a cup of water to make a solution and then half cover it with a piece of paper. They should discover a weaker effect of condensation warming (Figure 5d). This means that the evaporation rate of water in a solution is lower than that in pure water. In other words, the vapor pressure above a solution is lower than that above pure water. This effect is known as vapor pressure depression, a colligative property. To investigate this property further, students can test a number of solutions with different salt concentrations and collect data to test the validity of Raoult's Law.

All these examples demonstrate the incredible power of IR imaging for scientific inquiry. But there is a caveat. Although visualization is critical, observation does not automatically translate into learning. Sometimes, visual learning could even be impeded by “deceptive clarity” (Linn, Chang, Chiu, Zhang, & McElhaney, 2010), which suggests that visual memory could, in fact, create an illusion of understanding. To avoid these problems, this project will situate observation in the POE sequence. In a typical POE task, prediction elicits students' initial ideas, observation provides verifications or creates cognitive dissonance, and explanation reconciles conflicts or raises new questions. The detailed descriptions of the examples in Figures 1, 2, and 5 illuminate how each step of an IR experiment can be framed with the POE model.

## PRIOR WORK

This proposal stemmed from a project *Enhancing Engineering Education with Computational Thinking* (NSF 0918449, ~\$2.2M, 2009-2013) directed by Dr. Xie. The IR cameras purchased by that project were used to explore their educational applications. The **intellectual merit** of the project is that it studied how computational tools can infuse science into hands-on engineering. **Publications** of the project include a paper titled “Visualizing Chemistry with Infrared Imaging,” which the *Journal of Chemical Education* selected as the cover article (Figure 7) of the July 2011 issue (Xie, 2011b) and described it as “captivating, intriguing, and thought-provoking” (Jacobsen & Slocum, 2011). This paper also reported a persistent temperature gradient ( $<0.5\text{ }^{\circ}\text{C}$ ) in a cup of brine that had never been documented in scientific literature before. Another paper “Infrared Imaging for Inquiry-Based Learning” was selected by the *Physics Teacher* as a featured article (Xie & Hazzard, 2011). The project has created **broader impacts** in the field of IR imaging. For example, our collaboration with Linköping University and Uppsala University (Haglund et al., 2016; Schönborn et al., 2014) was reported by Swedish newspaper *Norrköpings Tidningar* on September 30, 2011, in a front-page story titled “Thermal cameras can become important in school physics” (Xie, 2011a). Our work has garnered interest from the industry as well. In 2012, Dr. Xie was invited to deliver a keynote presentation at the opening plenary session of InfraMation—the largest conference for IR thermography in the world. Recently, the CC team has started working with the BGSU team on advancing IR chemical imaging. The two teams have co-designed several IR experiments for chemical education from scratch and explored the feasibilities of using IR imaging to visualize lab experiments currently used in BGSU's chemistry courses. The fruitful collaboration between the two teams on IR chemical imaging laid the foundation for this proposal.

BGSU and CC have also collaborated on *Constructive Chemistry: Problem-Based Learning through Molecular Modeling* (NSF 1245356, ~\$250K, 2013-2015, PIs:



Figure 7. Upper: Our IR imaging experiments were featured on the cover of July 2011 issue of the *Journal of Chemical Education*. Lower: A high-throughput IR imaging experiment at BGSU to study the energetics of protein conformational change in various solutions.



Leontis, Torelli, & Xie). The **intellectual merit** of the project is that it explored molecular modeling as a constructionist pedagogy. The **broadier impacts** included the development of a causal diagram assessment technique for measuring students' molecular reasoning ability (Torelli & Xie, 2016). This technique can be computerized to support automatic assessment, which will be used and advanced in the proposed project.

## THE DEVELOPMENT PLAN

This section lays out our plan to develop the IR experiments and the instructional units. The development of formative assessment embedded in these units to guide and measure learning will be presented in the next section. As an option, each unit will begin with a brief introduction about how to use an IR camera and how the emissivity and reflectivity of a substance may affect an IR image. Knowing that low emissivity can create an illusion of low temperature and high reflectivity can create an illusion of high temperature is important to interpreting IR images correctly (though these will not be issues for most experiments we plan to include). If students have completed a unit before, this introduction can be skipped.

Table 1 outlines the seven laboratory units with the planned experiments. We have proven the preliminary designs of these experiments in our labs. Some of the ideas have been published in peer-reviewed journals (Xie, 2011b; Xie & Hazzard, 2011). Aside from the initial expenses of IR cameras, which as generic tools can be shared across departments, we will strive to keep the costs of materials and supplies needed for these experiments low in order to maximize their reproducibility in diverse settings. This consideration will broaden the impact of this project even to K-12 schools.

Table 1. Outlines of seven lab units (the images in the left column show an exemplary experiment of each unit).

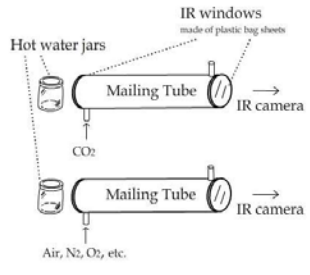
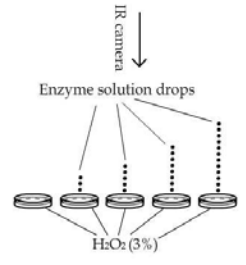
Unit	Basic Part	Extended Part
<p>Greenhouse gases</p> 	<p>Investigate the absorption of IR light by greenhouse gases such as CO<sub>2</sub>.</p> <p>A mailing tube filled with CO<sub>2</sub> will absorb IR light radiated from a heat source, impeding an IR camera's ability to see the heat source on the other side of the tube. The IR windows that seal the tube are made of plastic sheets from a grocery bag to let IR light go through.</p>	<p>Students test other gases to determine whether they are greenhouse gases. If possible, students also estimate the abilities of the gases to absorb IR light by comparing the temperature readings on the IR camera when it points to the heat source on the other side of the tube. (Note: Boston College has expressed a strong interest in adopting this experiment for explaining climate change to non-science majors if its development is funded.)</p>
<p>Enzyme kinetics</p> 	<p>Investigate enzyme kinetics using the enthalpy of the substrate reaction as a thermal indicator.</p> <p>Catalase is an enzyme that catalyzes the degradation of hydrogen peroxide in a reaction that can be easily visualized with an IR camera. The high-throughput nature of IR imaging allows students to investigate multiple parameters related to enzyme activity at once. For example, they can study the effect of increasing enzyme or substrate concentration on the rate of reaction or the time required to reach equilibrium by monitoring the surface temperature pattern of an array of parallel reactions using an IR camera and its image analysis software.</p>	<p>Students investigate enzyme kinetic parameters by analyzing the initial rate of reaction as a function of substrate concentration, the effect of varying pH on enzyme activity, or the effect of specific enzyme inhibitors on the reaction kinetics. They rationalize their data with the Michaelis–Menten formalism. Students also compare the efficiency of homologous enzymes sourced from different species. Although catalase found in both potato and liver produces O<sub>2</sub> bubbles that can be seen by the naked eye, IR imaging reveals a baffling difference in their energetics that may be overlooked without an IR camera: The reaction catalyzed by the enzyme from potato <i>appears</i> to be endothermic, as opposed to the case of liver in which the reaction is exothermic.</p>

Table 1. (Continued)

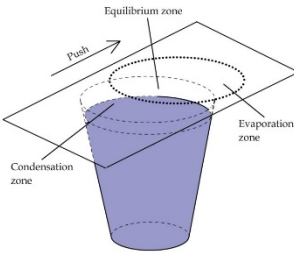
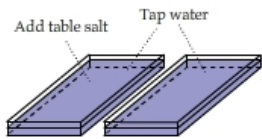
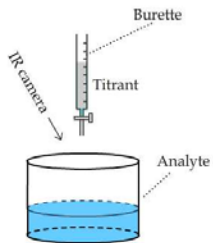
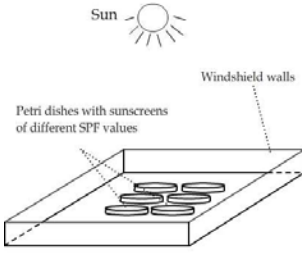
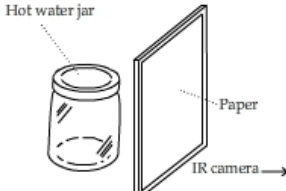
<p>Phase transition</p> 	<p>Investigate evaporation, condensation, melting, and freezing by observing their latent heats through IR imaging.</p> <p>Evaporation and condensation can be explored using a piece of paper and a cup of water (Xie, 2011b). The simple setup to the left creates a teachable moment where IR imaging is used to visualize both processes on a single piece of paper after the dynamic equilibrium between the two processes is broken by shifting the paper (which has been placed on top of the cup for a while before it is moved).</p>	<p>Students design experiments that visualize the latent heat of ice. For example, students can exploit the effect of freezing point depression to create a salt solution that does not freeze at <math>-10^{\circ}\text{C}</math>. Then pour the solution and pure water into two trays and refrigerate them at <math>-5^{\circ}\text{C}</math>. After the pure water has completely frozen into ice, students observe the trays using IR imaging. While the surface temperature of the solution rises quickly, the surface temperature of the ice remains low for some time, providing visual evidence of latent heat. Students can also try to freeze both solution and water at <math>-20^{\circ}\text{C}</math> or lower and study if there is a difference in their latent heats. The results can be quite counter-intuitive—the frozen salt solution actually warms up more slowly in this case, creating more inquiry opportunities.</p>
<p>Colligative properties</p> 	<p>Investigate vapor pressure depression, freezing point depression, and boiling point elevation.</p> <p>The temperature difference between pure water and a salt solution in two trays shown to the left can be used to visualize vapor pressure depression under an IR camera. In this case, <i>the heat of vaporization is used as a thermal indicator of vapor pressure</i>.</p>	<p>In the case of vapor pressure depression, students test multiple substances to examine if the same effect can be observed as in the case of using salt solution. Students change the concentration to study positive or negative deviations from Raoult's Law. Students devise experiments to visualize freezing point depression and boiling point elevation. The IR visualization of boiling point elevation using a tray of pure water and a tray of brine may provide a spectacular contrast because of the violent motions in boiling water.</p>
<p>Titration and reaction</p> 	<p>Learn titration and investigate reactions.</p> <p>The endpoint of a titration can be determined by analyzing the IR images of the surface of the liquid in the beaker as its temperature pattern varies in different stages of the titration.</p>	<p>While practicing titration in the lab, students also explore both endothermic and exothermic reactions and the effect of concentration on the reaction rate. As it is based on the idea of using the enthalpy of reaction to monitor a chemical reaction, this thermal imaging technique can also be used to teach the principle of thermometric titration (an alternative to potentiometric titration).</p>
<p>Light-matter interaction</p> 	<p>Investigate different substances' abilities to absorb light.</p> <p>The Sun Protection Factor (SPF) measures how well a sunscreen protects skin from UVB rays. Students apply different sunscreens to petri dishes, expose them under the sun for 10 minutes or longer, and then compare their temperatures using an IR camera to evaluate their relative abilities to absorb UVB.</p>	<p>Students explore the relationship between the color of a pigment and its ability to absorb sunlight (Figure 3). They use a prism to separate sunlight into different wavelengths and compare different pigments' abilities to absorb light of different colors. As shown in Figure 3, different pigments can be painted as color strips on a sheet of paper onto which refracted light projects.</p> <p>The sunscreen experiment is related to health and should interest the large number of pre-med and nursing students who take general chemistry courses at the participating institutions.</p>

Table 1. (Continued).

<p>Heat transfer</p> 	<p>Investigate three modes of heat transfer: conduction, convection, and radiation (Xie &amp; Hazzard, 2011).</p> <p>The radiation from a hot water jar to a piece of paper can be captured by an IR camera. Students can change the angle at which the paper faces the jar or the temperature of the jar (e.g., fill the jar with ice water) to study the dependence of thermal radiation on these factors.</p>	<p>Students find ways to distinguish the three different modes of heat transfer in real experiments or compare the heat transfer rates through the three modes. For example, students are challenged to design ways to measure the heat released through conduction, convection, and radiation, respectively, in a combustion process.</p> <p>(Note: We include heat transfer because it is covered in general chemistry at BGSU.)</p>
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The laboratory units will be structured using the POE cycle (Figure 8) at each step of experimentation. We call this kind of guided POE inquiry at a fine-grained level *micro-cycles*. A laboratory unit can consist of many micro-cycles. A clear definition of micro-cycles in the units allows researchers to identify them from student data dissected to understand the interactions among different learning objects and mechanisms (discussed in the Research Plan). In order for researchers to collect data for analysis, students will record their predictions, observations, and explanations in a Web-based system.

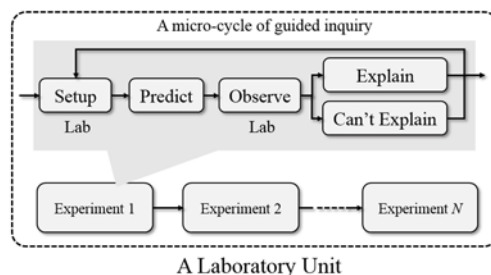


Figure 8. A laboratory unit consists of a series of experiments, each of which is based on multiple iterations of the POE cycle.

## THE RESEARCH PLAN

Our hypothesis that IR imaging can accelerate and deepen scientific inquiry through rapid data collection and immediate visual feedback agrees with earlier studies that suggest virtual experiments can enhance learning by facilitating faster manipulation compared to real experiments (Klahr, Triona, & Williams, 2007; Zacharia, Olympiou, & Papaevripidou, 2008). We are particularly interested in studying the extent to which the visual, interactive, and iterative benefits claimed for virtual experiments can also be provided by IR imaging for real experiments. From the unique perspective of scientific imaging of natural phenomena rather than computer simulations, this research will contribute to the body of knowledge about using scientific visualization in science education (Gilbert, 2005).

## Participants

We have received enthusiastic responses from faculty members of six other institutions (Table 2). Among them, Parkland College and Bradley University have already purchased or done work with IR cameras. Over the three project years, we expect that more than 1,000 students from these institutions will be involved in this research. For the fidelity of our research, we will ascertain that all the students have fair access to IR cameras. If funded, BGSU and CC will each purchase 20-30 cameras for this project. In addition to the 40 IR cameras that CC currently owns, we will have about 90 cameras that can be loaned to the partnering institutions on a rotating basis.

Table 2. More than 1,000 students from the following institutions will participate in this project over three years.

Institution	Contact	# Students	Type
Boston College (MA)	Dunwei Wang	57 (Non-science majors)	Four-year
Bowling Green State (OH)	Peter Blass	200 (Science/health majors)	Four-year
Bradley University (IL)	Dean Campbell	200 (Science/health majors)	Four-year
Owens Community College (OH)	Joanna Smithback	100 (Science/health majors)	Two-year
Parkland College (IL)	David Wilson	300 (Science/health majors)	Two-year
St. John Fisher College (NY)	Andrea Bills	60 (Chemistry majors)	Four-year

SUNY Geneseo (NY)	Jeffrey Peterson	200 (Science/health majors)	Four-year
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## Data Sources and Research Instruments

To measure and analyze student learning, this research will include a quantitative part based on pre/post-tests partially drawn from existing concept inventories and causal diagram construction derived from concept map assessment, as well as a qualitative part based on IR image analysis, faculty survey, student interview, and video case studies. Table 3 provides additional details.

Table 3. Data sources and instruments for finding evidence of learning and the underlying cognitive mechanisms.

Data Source	Instruments
<b>Pre/post-tests</b> (quantitative)	Applicable items selected from existing chemistry concept inventories (Krause, Birk, Bauer, Jenkins, & Pavelich, 2004; Mulford & Robinson, 2002) and energy/heat concept inventories (Jacobi, Martin, Mitchell, & Newell, 2003; Prince, Vigeant, & Nottis, 2012; Swackhamer & Hestenes, 2002). Participating faculty will review the selected items and contribute additional items that fit their courses.
<b>Embedded assessment</b> (quantitative)	Causal diagram construction (Torelli & Xie, 2016) that measures student ability to organize discrete concepts into a coherent explanation.
<b>Student actions</b> (qualitative)	Video recordings and follow-up interviews of purposively selected student groups.
<b>Lab reports</b> (qualitative)	IR images, prediction/observation/explanation notes, questions asked, hypotheses proposed, number of variables explored, and variations of experiments tried.
<b>Faculty survey</b> (qualitative)	Instructors' opinions of IR laboratory experiences and student learning outcomes compared to those from previous years when IR imaging was not used.

Causal diagram construction as an embedded formative assessment technique that guides chemistry experiments and measures conceptual learning will be an innovation of this research. According to the Knowledge-in-Pieces Theory (diSessa, 1988, 2014) and the Knowledge Integration Theory (Linn & Eylon, 2011), students often start with fragmented knowledge acquired from different sources, and deeper learning can be viewed as a process of integrating isolated pieces of knowledge. Constructing a causal diagram to

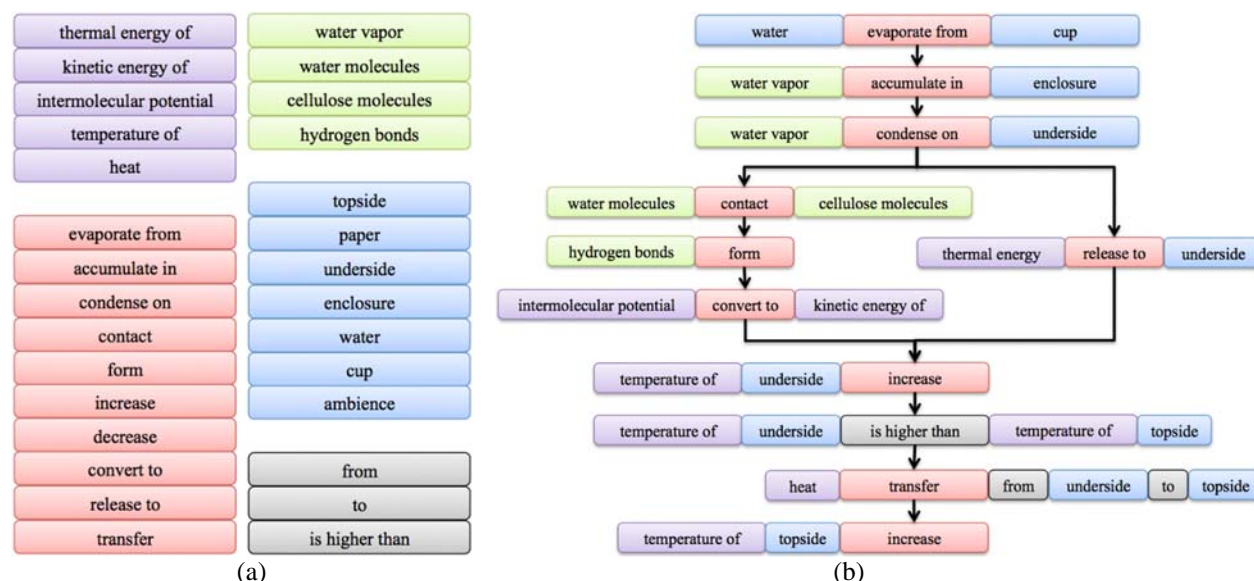


Figure 9. Graphically constructing an explanation of the effect of condensation and adsorption warming on a piece of paper above a cup of water using a causal diagram representation. This Web-based assessment tool resembles the graphical programming interface of Scratch, allowing students to assemble a set of knowledge pieces that are originally randomly placed (a) into a connected diagram that explains a chemical phenomenon (b). The constructed diagram can then be automatically analyzed to provide an assessment of the student's knowledge integration.



explain a chemical phenomenon provides a way for students to assemble disparate concepts into a logical network of causality. The degree to which this network matches an expert's view represents the student's knowledge state. These theoretical considerations give rise to causal diagram construction, a variation of concept map assessment (Barenholz & Tamir, 1992; McClure et al., 1999) that we are developing for assessing conceptual understanding of chemistry in a previous project (Torelli & Xie, 2016). A computerized version of this technique will be developed based on some prior Web programming work in this direction done at CC. It will provide a Web-based interface that supports students in constructing an explanation of an observation graphically (Figure 9), similar to using a graphic organizer to help students solve aqueous acid–base equilibrium problems (DeMeo, 2007). The causal diagrams constructed by students will be automatically assessed using computer algorithms based on graph theory (Xie, 2015), a significant advantage that saves time for human scoring and eliminates possible human errors.

### Cognitive Mechanisms Catalyzed by Infrared Imaging

To inform future development of curriculum and pedagogy based on imaging technologies, we will also investigate the cognitive mechanisms underlying the learning processes supported by IR imaging. As pointed out earlier, IR imaging can render real-time full-field visualization, accelerate data collection, and induce cognitive conflicts. These affordances can potentially optimize inquiry-based learning by instigating and maintaining curiosity, streamlining inquiry processes, and mediating scientific augmentation among students. The combination of these affordances engenders the unique ability of IR imaging to catalyze cognitive conflicts with memorable visualizations of real-world phenomena. In the previous sections, we have mentioned four instances of cognitive conflicts that students may encounter in the simple IR experiments described in Figures 1, 2, and 5. Some of these cognitive conflicts would have been difficult to reproduce without the use of an IR camera.

Figure 10 shows a hypothetical model of how a group of students may decipher the warming effect shown in Figure 5a through multiple micro-cycles of POE driven by IR imaging. To substantiate and further improve this hypothetical learning model, we will conduct case studies with a small number of student groups that are purposively selected to represent the varying levels of science competency and the learning contexts in different partnering institutions. The lab sessions of these selected groups will be video recorded to capture the details of their inquiry processes. These student groups will also be interviewed after each lab session to retrospectively report and reflect upon their learning. These two data sources will be analyzed jointly using a microgenetic learning analysis method (Parnafes & diSessa, 2013).

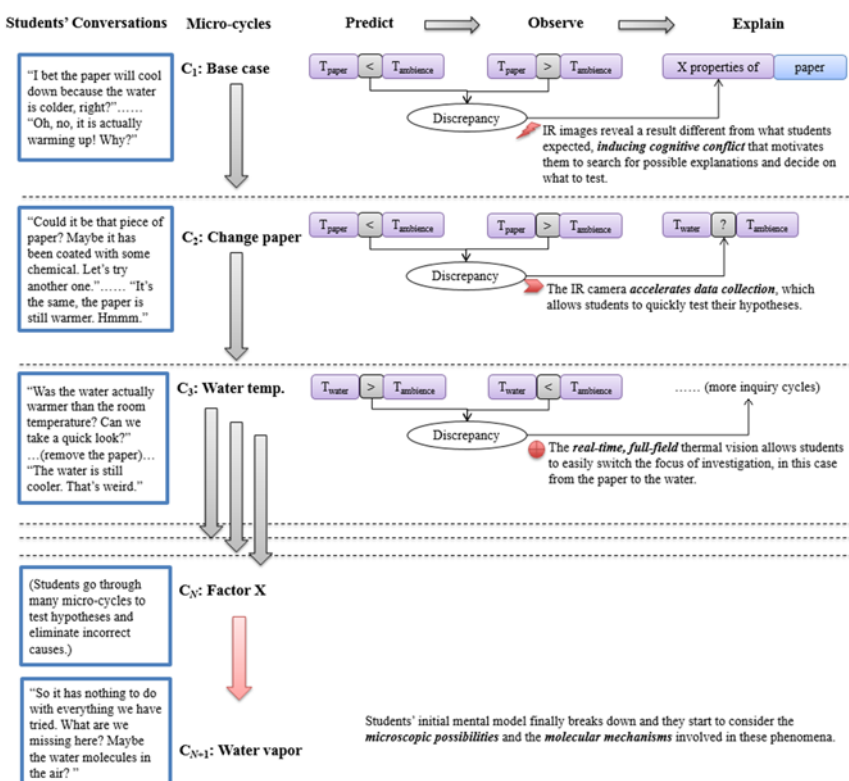


Figure 10. A hypothetical scenario based on the micro-cycle POE model with the affordances of IR imaging highlighted.

Specifically, the recorded videos will be transcribed and segmented into POE micro-cycles (Derry et al., 2010). Each segment will be analyzed to identify the focal objects, concepts, and procedures attended to by students as well as the elements of scientific augmentation (e.g., claim, evidence, and reasoning) invoked by students (Berland & Reiser, 2009). Meanwhile, cognitive mechanisms will be inductively distilled from the connections of knowledge pieces and the progressions of POE cycles mediated by IR imaging (Kozma, Chin, Russell, & Marx, 2000). The interview data will be used to supplement and triangulate the video data throughout the analysis process. The results will be compared to the idealized learning model to identify where it may need to be modified, in accordance with the principles of design-based research.

## PROJECT TIMELINE AND MANAGEMENT

This project is scheduled as follows:

- **October 1, 2016-September 30, 2017:** We will develop and refine the IR experiments listed in Table 1, the lab units with POE tasks, the causal diagram tasks, and other research instruments such as pre/post-tests. We will administer pilot tests in chemistry classes at BGSU.
- **October 1, 2017-September 30, 2018:** We will scale up the implementation and research to include the six other institutions. We will hold a one-day workshop to introduce the lab units and the educational research to the participants. Based on the initial results and feedback, we will revise all the IR experiments, the instructional materials, and the research techniques.
- **October 1, 2018-September 30, 2019:** We will carry out another round of scale-up study. Meanwhile, we will analyze the data collected from the previous years and submit the results for publication.

## PROJECT PERSONNEL

### The Advisory Board

An Advisory Board will review the IR imaging experiments, the laboratory units, and the research findings and provide high-level feedback to project staff. Due to budgetary limitations, we will not have a designated external evaluator and will instead rely on the Advisory Board to evaluate the project. In order to conduct the evaluation, the Advisory Board will work with the project team to define a matrix of tasks, goals, and timelines. At the meetings with the Advisory Board, project staff will present the progress of each task in detail, followed by questions and discussions from the board members to help gauge the evaluation indicators. The members will compile an evaluation report after each meeting that will include recommendations addressed to the staff and forwarded to the cognizant program officer. The five members are:

- **Dave Bursell** is Vice President of FLIR Systems, a global leader of IR technologies. His 12 years of experience as the Director of Science of FLIR will be a great resource for this project.
- **Dr. David Clarke** is Professor of Materials at Harvard University. He has been involved in many different materials research and development programs, contributing to ceramics, metals, composites, and semiconductors. He is author or co-author of more than 350 papers, holder of six patents, and a member of the National Academy of Engineering. He is interested in using IR cameras in his own teaching.
- **Dr. George Lisensky** is Professor of Chemistry at Beloit College. He has extensive experience in scientific visualization and experiment design in the areas of materials, solids, nanochemistry, inorganic chemistry, and analytical chemistry. He regularly teaches laboratory sections and is actively involved in developing ways to use new technologies in chemistry education.
- **Dr. Ji Shen** is Associate Professor of Science Education at the University of Miami. His research includes developing innovative, technology-enhanced learning environments, interdisciplinary science learning and assessment, and modeling-based teaching and learning.
- **Dr. Angelica Stacy** is Professor of Chemistry at the University of California, Berkeley. Her research focuses on the synthesis of materials with novel properties that can be applied to emerging technologies and elucidate their behavior. She is also interested in promoting chemistry education at all levels.

### Staff at Bowling Green State University

- **Dr. Andrew Torelli**, Assistant Professor of Chemistry, will serve as the PI at BGSU. He is trained in macromolecular X-ray crystallography and has actively participated in multiple opportunities to improve undergraduate chemistry education. He is a member of the BGSU Faculty Learning Community for increasing student learning through strategic assessment in STEM education. He has also designed several IR imaging experiments for general and introductory chemistry courses. Dr. Torelli holds a Ph.D. in structural biology from the University of Rochester.
- **Dr. Alexis Ostrowski**, Assistant Professor, will serve as a Co-PI. She has been involved in chemical education initiatives since graduate school and is especially interested in activities that promote diversity in STEM fields. Alexis has received two awards in 2010 for her work with K-12 programs and diversity in science. She teaches general chemistry and inorganic chemistry and has developed photochemical experiments and absorbance measurements for the courses. Dr. Ostrowski holds a Ph.D. in materials chemistry from the University of California, Santa Barbara.
- **Dr. Peter Blass**, Lecturer of Chemistry, will pilot-test the laboratory units at BGSU. He works on development of online materials for general chemistry and is interested in remediation of common misconceptions in science. He has promoted peer-to-peer and mentor-led teaching to significant effects. Dr. Blass holds a Ph.D. in chemical physics from the University of Texas at Austin.

### Staff at the Concord Consortium

- **Dr. Charles Xie** will serve as the PI at CC. A Fellow of the International Society of Design and Development in Education, he has 16 years of research and development experiences in software, hardware, and curriculum. As a developer, he has created four popular scientific simulation tools and invented unique mixed-reality technologies. As a researcher, he has published over 20 papers in peer-reviewed journals. His pioneering work on IR imaging has earned him recognition from the industry. Dr. Xie holds a Ph.D. in materials science from the University of Science and Technology Beijing.
- **Dr. Jie Chao** will serve as an educational researcher. As a learning scientist, she has led multiple research projects on how innovative learning technologies can improve conceptual understanding in science and engineering. She holds a B.S. in chemistry from Peking University and a Ph.D. in instructional technology in STEM education from the University of Virginia.
- **Dr. Corey Schimpf** will serve as an educational researcher. He has experience researching how innovative learning technologies affect college students' conceptual understanding and practices in science and engineering. His dissertation investigated how learning technology influenced student-centered inquiry practices. He holds a Ph.D. in engineering education from Purdue University.

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