Transforming Science Education with IR Imaging

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ABSTRACT

Scientists have long relied on powerful imaging techniques to see things invisible to the naked eye and thus advance science. Scientific imaging such as IR imaging represents a new generation of inquiry technology that shows great potential in fostering science education. This paper presents an initiative of introducing IR cameras to science labs in schools to empower students to make authentic scientific discoveries. It demonstrates how advanced technologies developed by industry to solve engineering problems can be converted into effective learning technologies to solve educational problems.

INTRODUCTION

The adage “a picture is worth a thousand words” underlines the importance of visual learning in education. IR imaging provides rich visual information about an ongoing process that can be rapidly recognized (this is the very same reason why IR thermography is such a revolutionary tool for industrial applications). Salient, real-time IR visualizations of unseen energy flows make the underlying concepts “speak for themselves” and can spur students to explore them more deeply.

In 1985, Prof. Gaalen Erickson at the University of British Columbia, wrote on page 59 in a book titled with *Children’s Ideas in Science* [1]: “If pupils were able to ‘see’ this phenomenon [that metals feel cold] in terms of a transfer of energy from their body to the object, this sort of situation would likely be less of a problem than it seems to be at present.” He was addressing a common misconception among students that metals are either by nature a cold substance or they are more capable of attracting cold from the surrounding air.

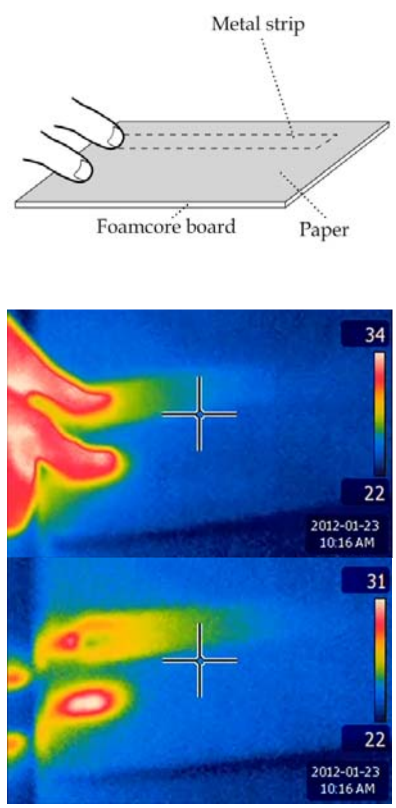


Figure 1: This experiment shows a comparison of thermal conductivities of metals and foams. A thin aluminum strip was placed on top of a foamcore board. They were covered up by a piece of paper to eliminate the effect of different emissivities of the metal and the foam. The two fingers were used as identical heaters.

More than twenty years later, Prof. Erickson’s wish has finally come true in schools, thanks to a much lower price tag for an IR camera. The IR experiment shown in Figure 1 enables cognitive scientists and educational researchers to study the efficacy of IR imaging and test Erickson’s hypothesis [2]. This experiment looks very simple, but it induced a cognitive conflict [3] between visual and tactile inputs: The IR visualization shows that the aluminum strip actually appeared to be warmer than the foam board after the thumbs touched them (the upper thermogram in Figure 1), creating a discrepancy with the sense of touch that suggested otherwise. By lifting the thumbs and then observing the IR patterns of the residual thermal energy in the metal and in the foam (the lower thermogram in Figure 1), the difference in the thermal conductivities—the key concept to resolve this cognitive dissonance —became apparent.

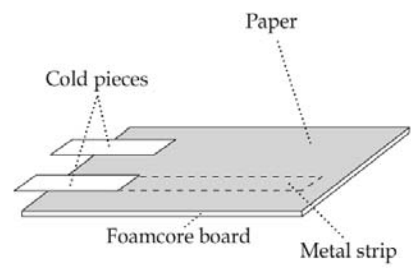
The power of IR imaging is much beyond what is illustrated in this example of thermal conduction. In a broad sense, easy-to-use IR cameras like FLIR’s I-series have engendered a new teaching and learning approach that promises to rapidly get science concepts across to students [4-6]. Thermal energy can be readily “seen” through an IR camera. Other types of energy that transform into thermal energy can be *inferred* from changes in thermograms. This capacity allows many invisible physical, chemical, and biological processes that absorb or release heat to be visualized, discovered, and investigated. In a way, this technology creates an abundance of learning opportunities for students that have never been experienced in the classroom before.

This paper will show, through selected examples in physics, chemistry, biology, and environmental science, how this new approach can make a large variety of scientific experiments easier for students to conduct, observe, and extend. These examples do not require quantitative analysis and are simple enough for anyone who has an IR camera to try quickly. We have written this paper in such a style that avoids excessive theoretical depths so that anyone with a high school science background can understand the scientific implications of these experiments. Each example is driven by a question to make it more investigative and interesting to the reader.

Some of the experiments are related to the science of applied IR thermography. Professional thermographers may also find them useful. For instance, the hands-on experiment shown in Figure 1 could be used in an IR thermography training course to teach the concept of thermal bridges as the aluminum strip beneath the paper could be imagined as a steel stud in a wall. Even if an example is not immediately related to building thermography or condition monitoring, it might still serve as an eye-opening introduction to what IR cameras are capable of doing beyond conventional applications.

HEAT TRANSFER EXPERIMENTS

Needless to say, thermography is a powerful tool for teaching and learning heat transfer. IR thermography not only provides a visual way to explain heat transfer but also teach students practical skills that are on greentech employers' wish list. In this section, we will show a set of experiments that cover conduction, convection, radiation, heat capacity, and light absorption.



Do metals always feel colder than foams?

The experiment in Figure 1 explains why metals feel colder than foams at room temperature (22°C). If we stop right there, many students might walk away with another misconception that metals *always* feel colder than foams. But is that true? Absolutely not! You may have experienced that outdoor metal handrails feel hotter than wood handrails in a very hot summer day.

A simple experiment shown in Figure 2 illustrates this phenomenon. While it does not make sense to raise room temperature to significantly higher above body temperature just to create artificial hot weather, we can simulate the situation by using two dry cold pieces (e.g., metal pieces wrapped with paper and stored in a freezer) and pretending that they were fingers. The thermograms in Figure 2 look like the "negatives" of the thermograms in Figure 1. To a naïve observer, it appears that, just like the common sense that heat flows from hot areas to cold areas, cold could flow as well—but in the opposite direction. If those two cold pieces were your fingers, you would feel that the finger above the metal strip was "losing cold," or warming up, faster. Of course, we know there is no such physical quality as "cold." It is just a layperson's term for describing a negative change of thermal energy, which to the conventional meaning of heat is just like a negative number to a positive number. A higher thermal conductivity results in a greater rate of change in thermal energy and this change can go in both ways—either losing or gaining heat.

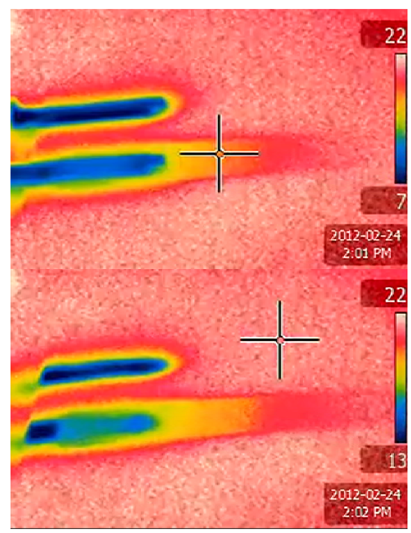


Figure 2: This experiment is approximately opposite to the one described in Figure 1. Thermography creates an illusion as if cold could also flow just like heat. In the upper thermogram, the two cold pieces were laid on the setup. In the lower one, they had been removed.

All these details are rarely written in textbooks, but they can lead students to a deeper understanding of thermal conduction and situate it in a more coherent context of heat and temperature. For thermography trainees, the experiment in Figure 2 could be used to explain why thermal bridges cost additional energy for air conditioning in summer.

Why do real leaves feel colder than fake leaves?

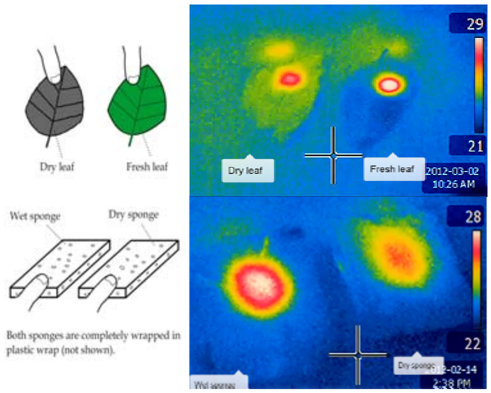


Figure 3: These two experiments compared the heat transfer from fingers to a dry leaf and a fresh leaf (upper) and to a wet sponge and a dry sponge (lower).It was shown that more heat transferred to a fresh leaf than to a dry one, and to a wet sponge than to a dry one, suggesting the role of water content on storing thermal energy.

One way to tell if an indoor plant is a plastic fake or a real one is to touch its leaves. Have you wondered why real leaves feel cooler? If you look at the leaves, fake or real, through an IR camera, you will see nothing because both are settled at the ambient temperature. So why does a real leaf feel colder than a fake one, if they are indeed at the same temperature?

The key is the extra heat capacity resulting from water contained in real leaves. The first experiment (the upper images in Figure 3) shows the thermograms of a fresh leaf and a dry one after being warmed up by fingers. It is clear that the reason that causes real leaves to feel colder is not because of the difference in thermal conductivities as shown in the case of metals vs. foams (Figure 1). Rather, it is caused by the fact that a fresh leaf is capable of absorbing more heat from a finger. This difference comes from the water stored in the spongy layer of a fresh leaf that a dry leaf has lost. To confirm this theory, we did another experiment using a wet sponge to simulate a fresh leaf and a dry sponge to simulate a dry leaf (the lower images in Figure 3). To stop water evaporation from the wet sponge and, therefore, the evaporative cooling effect, we used plastic film to wrap it up. The dry sponge was also wrapped to ensure identical emissivity. The thermograms of the sponges show a similar difference as is in the case of the leaves.

The effect of heat capacity on heat transfer explains why hypothermia is more likely in cold water than in cold air. This may also be a factor that thermographers must take into account when analyzing thermograms. For thermography training, the experiments in Figure 3 could be extended to compare different construction materials (e.g., stone vs. plastic) to provide hands-on opportunities for trainees to see the concept at work.

Can we see air convection?

Air convection cannot be seen directly because air is invisible, but it can be visualized using an IR camera: The temperature field approximately represents the air current because the thermal buoyancy that drives the current at a given location is approximately proportional to the temperature at that point relative to the ambient temperature. Figure 4 shows an apparatus in which a rotatable screen can be used to take different “slice views” of the three-dimensional flow. The screen is a thin fiberglass or nylon wire mesh through which air flows to heat it up or cool it down quickly. When the screen is upright above a heater, the rising hot air will warm it up and create a trace of convection from the bottom to the top, which can be seen through an IR camera. At the horizontal position, the thermogram of the screen shows the cross section of the rising heat plume.

If a larger screen is used, this technique could even be generalized to monitor ventilation in a room, as described by Raphaël, Pastor, and Thunevin in an FLIR technical report [7].

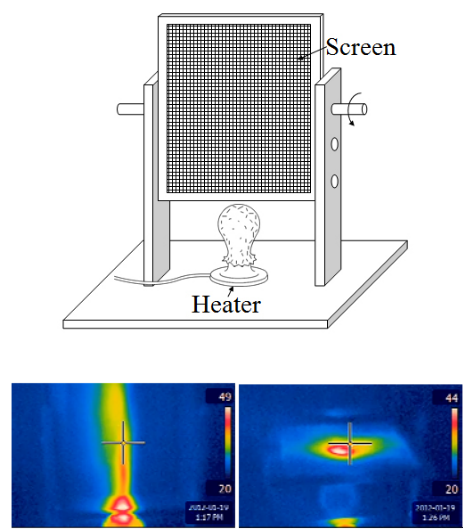


Figure 4: A screen to capture the three-dimensional heat flow through natural convection from a heater.

Why do we feel cold when facing a cold object?

As thermal radiation goes both ways between two objects, the radiative heat transfer is the net flux of radiant energy from one to the other. The reason why we feel cold when facing a cold object (e.g., a window in winter) is because the face radiates more energy to the cold object than the cold object to the face. This is often not intuitive to students. The experiment in Figure 5 was designed to visualize this effect.

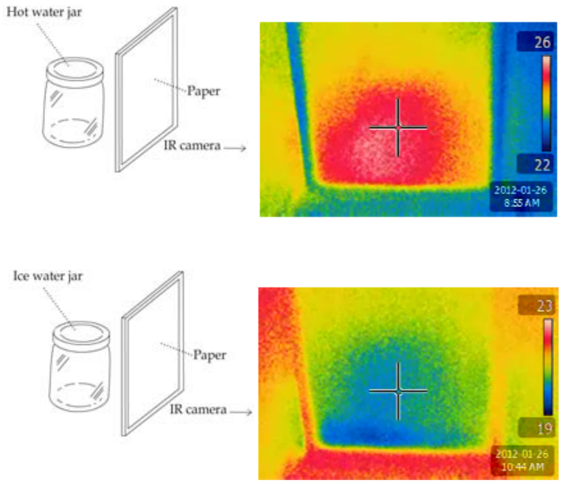


Figure 5: Radiation heat transfer between a hot water jar (~70°C) and a paper screen (upper images) and between an ice water jar (~5°C) and a paper screen (lower images).

The experiment used a “radiation projection screen,” which was simply a piece of paper. The radiative heat transfer occurred between a jar filled with hot or cold water and the paper screen. To avoid getting direct radiation from the jar, the IR camera was aimed at the other side of the screen. Because the screen was thin, radiant heat would be conducted from one side to the other quickly to be captured by the camera.

How can we be sure that thermograms we observed were caused by thermal radiation? If we wrap the hot or cold water jar with aluminum foil that has very low emissivity but very high reflectivity, the red or blue column in the thermal image of the screen will diminish significantly and its temperature will become close to the ambient temperature. This is because the aluminum foil reflects the ambient radiation to the screen. This extended experiment could be used to illustrate how radiant barriers work to save energy in both winter and summer conditions.

Which color absorbs more light energy?

Everyone knows black absorbs more light energy than white. What about other colors? Thermography offers a fun solution: Just use your word processor to print a page with different color bars, put it under the sun, and point your IR camera at it. The thermogram immediately shows the difference in the abilities of the color bars to absorb light energy (Figure 6). In a thermography class, the instructor could use the idea of this experiment to compare the performances of different roof paints, for instance.

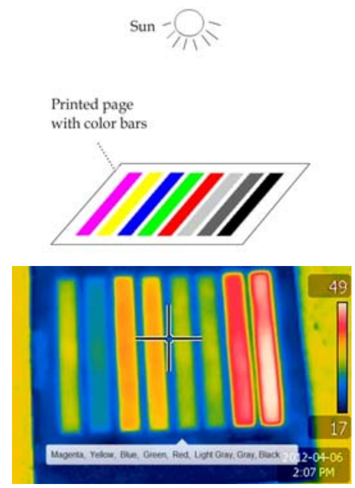


Figure 6: Comparing light absorption of different colors.

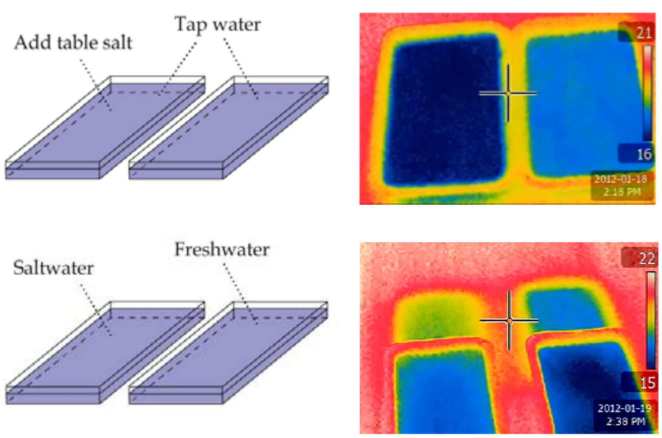


Figure 7: The upper images show water cooled down when salt was added. The lower images show, after the salt was completely dissolved, that the saltwater became warmer. (The lower thermogram shows that the foam board surface below the freshwater container was also cooler, suggesting that this effect was not due to a possible difference in emissivity, if any, caused by the added salt ions.)

CHEMISTRY EXPERIMENTS

Heat is a central concept in chemistry. In most cases, a chemical reaction is either endothermic (absorb heat) or exothermic (release heat). To some extent, therefore, heat can be regarded as some kind of “ink” that allows us to track the process of a reaction. In this section, we will show how IR cameras can be used to visualize chemistry.

Why does saltwater in a container become warmer than freshwater?

High school chemistry tells us that the dissolving of table salt (NaCl) is endothermic. With an IR camera, we can easily show this cooling effect when we add salt to water, as shown in the upper images in Figure 7.

What is more interesting in the experiment is that, a few hours later, the temperature difference was reversed: Now the freshwater became cooler than the saltwater! The lower images in Figure 7 show this. Since there was no ongoing reaction after salt was completely dissolved, the only sensible explanation is that the effect of evaporative cooling slowed down in saltwater. This is actually known in chemistry as *vapor pressure lowering*: Whenever there is a non-volatile solute present in a solution, water molecules cannot escape as easily as in pure water, resulting in a lower vapor pressure above the solution.

Why do people spread salt on the roads in winter?

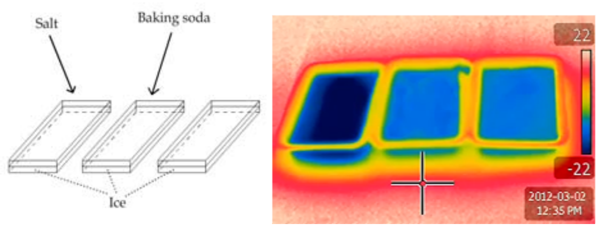


Figure 8: This thermogram shows that adding salt to ice resulted in cooling that was much more significant than adding baking soda to ice.

Northern states spread tons of salt every winter to keep the roads ice-free. If you happen to run out of salt one day, would it be a good idea to spread baking soda or sugar on your driveway instead? The simple experiment in Figure 8 will tell you that it is probably not a great idea if you need to get rid of the ice quickly.

Through an IR camera, you can directly observe an extraordinary cooling phenomenon. In our experiment, we found that, when table salt was added to ice, it immediately melted the ice. The melting process absorbed so much energy that the temperature of the produced saltwater dropped more than 10°C in just a few seconds! No wonder this method is still used to freeze the ice cream mixture for making ice cream at home quickly.

As we have seen from Figure 7, dissolving salt in water results in cooling, but the degree is not sufficient to explain this dramatic cooling effect. The effect actually includes the contribution from the latent heat absorbed to melt the ice. To prove this further, the next experiment will show the opposite of this process.

Why does saltwater warm up faster than ice?

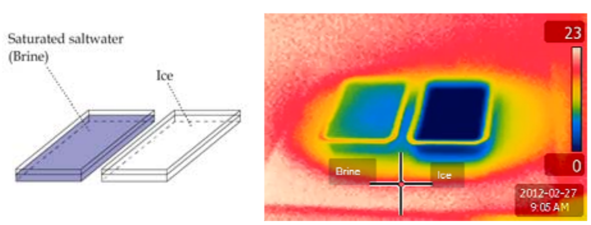


Figure 9: This thermogram shows (unfrozen) saltwater warmed up more quickly than ice. Their initial temperatures were the same.

We put a container of high-concentration saltwater (brine) and a container of freshwater in the freezer for at least 10 hours. The temperature of the freezer was enough to freeze the freshwater but not the saltwater. We then took them out, let them warm up at room temperature, and observed the warming process through an IR camera. The temperature of the saltwater container was found to rise much faster than that of the ice container.

This difference demonstrates the latent heat of ice. The melting of the ice prevented the temperature from rising quickly because it needed to absorb a lot of thermal energy to break down the chemical forces that fixed water molecules in the ice crystal, whereas in the liquid saltwater, all the absorbed thermal energy was used to increase its temperature.

What warms up a piece of paper when it approaches water?

In the experiment illustrated in Figure 10, a strip of paper (or cardstock) approached (but did not touch) the surface of water from the vertical direction. Viewed through an IR camera, the paper warmed up as if it had

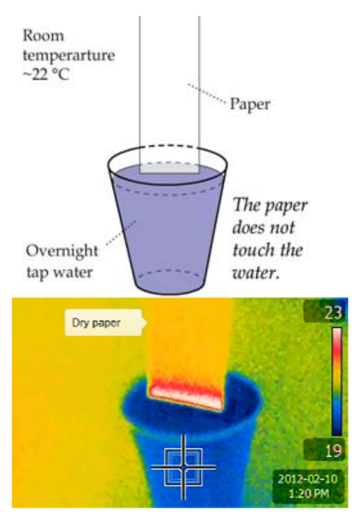


Figure 10: A piece of paper warmed up when it approached, but did not touch, water in a cup.

caught a fire. Considering that water was cooler than the paper—due to the evaporative cooling effect—as shown in the thermogram, it appeared that heat were able to go against the temperature gradient and transfer from water to paper. We know heat cannot spontaneously flow from a cold object to a hot object. So what caused this strange phenomenon?

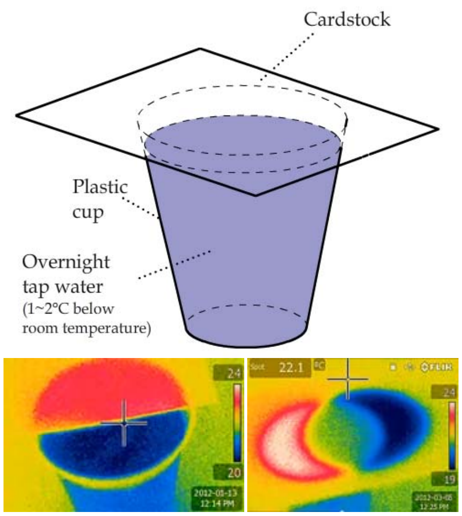


Figure 11: A piece of paper or cardstock warmed up when it was put above a cup of water. Shifting it resulted in a thermogram that simultaneously showed heating and cooling related to latent heat.

Although we cannot see, there are water molecules constantly evaporating from an open cup filled with water. These molecules are in a gaseous state and carry higher energy away, which explains the effect of evaporative cooling. Once air-born, these molecules collide with air molecules and move in random directions. When they run into a rough, hydrophilic (water-loving) surface such as a piece of paper, they will stick to it and give their extra energy to the cellulose molecules of the paper. This process continues as more water molecules land on the paper surface and condense into numerous tiny liquid drops, resulting in significant heating due to the latent heat released by condensation. To understand this, just imagine that the heat your body loses to evaporation when you just get out of a swimming pool returns to warm you up if the water molecules in the air could find a way to condense back on your skin.

At this point you may feel that the above statement is just a theory. How can we be sure that this actually happens? Let's see another experiment. This time we laid the paper (or cardstock) on top of the cup (Figure 11). We observed a similar heating phenomenon in the area of the paper above water (the thermogram on the left in Figure 11). What is more interesting is the thermogram taken when we shifted the paper after it fully covered the cup and rested in that position for 10-20 minutes (the image on the right in Figure 11). This thermogram shows that the paper exhibited *four* distinct zones that were at different temperatures! They were represented by four different colors: white, blue, green, and yellow (which represented the ambient temperature). As theorized above, the heating in the crescent-shaped white zone was caused by water molecules that condensed onto the dry area of the paper that just entered the cup circle. What about the cooling in the complementary crescent-shaped blue zone? This is actually the evidence that there had been water condensate (dew) on the underside of the paper. Since that area exited the cup circle, the water molecules in those tiny dews started to evaporate, cooling the area down. It is amazing to note that this experiment simultaneously caught the absorption and release of latent heat in two concurrent phase changes. Such an interesting phenomenon would have gone unnoticed without an IR camera.

The science that a piece of paper and a cup of water can demonstrate under an IR camera is surprisingly plentiful. There are many extensions of this experiment that allow students to explore further. For example, one can use a plastic strip to approach water and find there is no heating effect, which leads to a discussion about what substrate is good for attracting water molecules (and wetting the surface). One can also use this experiment to check the effect of vapor pressure lowering by putting two pieces of paper above a cup of saltwater and a cup of freshwater. Due to the weakening of evaporation from saltwater, the heating of paper above saltwater will be less significant than that above freshwater. Students can also investigate the relationship between the temperature of the water and the heating of the paper.

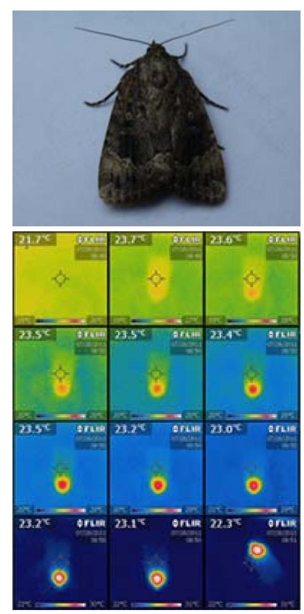


Figure 12: A sequence of IR images showing the thermogenesis of a moth at the thorax. Note that automatic color remapping was used to increase the contrast of these images.

BIOLOGY EXPERIMENTS

IR imaging has been widely used to film and study animal and plant behaviors, as often seen on Discovery Channel or Animal Planet. Why not just give this powerful tool to children and let them discover the biology themselves in their gardens and parks? In this section, we will show some examples.

Are insects always cold-blooded?

Are insects warm-blooded or cold-blooded? If you google this, some would tell you they are cold-blooded. That is not entirely true. Figure 12 shows how a moth warmed up while it was getting ready to fly. So at least a moth is warm-blooded when it moves.

The first IR image shows that when it was idle, its body temperature agreed with the ambient temperature. This means that it did not lose heat to the environment while sleeping—a clever strategy for saving energy and protecting itself from predators with IR vision. In order to see the moth, we blew some hot air towards it so that its body shape could be recognized through the IR camera. The thermograms show that, to make a move, the moth needed to heat up its flight muscles to above 30°C. In this observation, the warming process took 1-2 minutes. The last image shows that the temperature was ready and the moth started to move. In this particular case, the moth responded slowly because it had been exhausted.

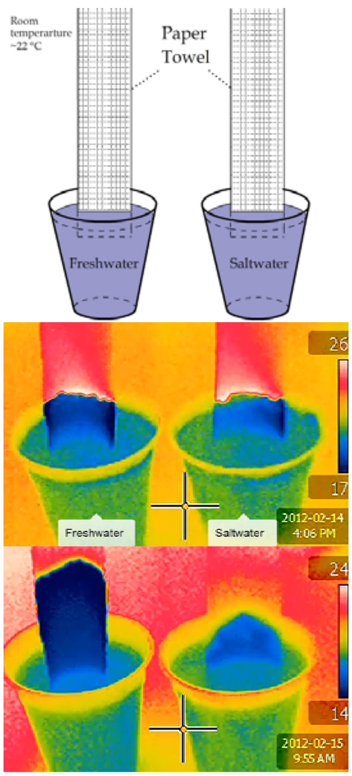


Figure 13: Capillary actions of freshwater and saltwater in two strips of paper towel caught by an IR camera. The upper thermogram was taken when the strips came into touch with water. The lower one was taken 18 hours later.

With a non-touch IR camera, children can discover similar thermogenesis in other flying insects such as bees, wasps, butterflies, and dragonflies without disturbing them or risking being stung by them.

Can salt ions be transported through capillary action?

Plants transport water, together with dissolved minerals, from the ground to branches and leaves through capillary action in xylem conduits. The experiment in Figure 13 simulates that mechanism using two strips of paper towel hung above a cup of freshwater and a cup of saltwater, respectively, to compare the capillary rises with and without salt ions.

Water diffused to a higher level in both strips but the IR color of the strip above the saltwater appeared to be less blue, suggesting that the evaporation of water was weaker on it. If you remember the effect of vapor pressure lowering discussed earlier, this difference is evidence of the diffusion of ions from the saltwater into the paper towel.

Many hours later, the salt ions that had diffused up accumulated enough to crystallize and block the capillary pathway. As a result, the upper part dried up completely. This could be a reason why saltwater kills some plants.

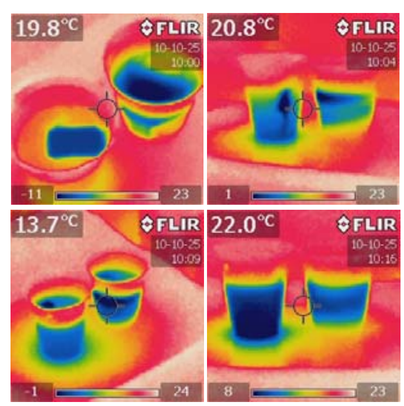


Figure 14: Seeing the thermohaline stratification. This experiment used just a cup of tap water, a cup of salt water, and some ice cubes. The two cups were placed next to each other on a table for comparison.

ENVIRONMENTAL SCIENCE EXPERIMENTS

The dynamics of climate is largely driven by heat. Considering the importance of climate change to the sustainability of our society, it is imperative that we teach our children in schools the environmental consequences of our actions. IR cameras can visualize some of these consequences and the scientific mechanisms behind them.

What slows convection in saltwater?

Did you know that ice melts much faster in freshwater than in saltwater? This seems to be at odd with the experiment in Figure 8 that shows solid salt can melt ice rapidly.

The experiment in Figure 14, which compared the melting of an ice cube in a cup of freshwater and the melting of an ice cube in a cup of saltwater, shows this effect and gives an explanation: The thermal convection in the cup of saltwater was much less significant, which slowed down the heat exchange between the ice cube and the water far below it and, therefore, the melting of the ice. Furthermore, this experiment demonstrated the effect of thermohaline stratification—a layered structure that has different salinity and temperature at different depths, which is an important phenomenon in marine science.

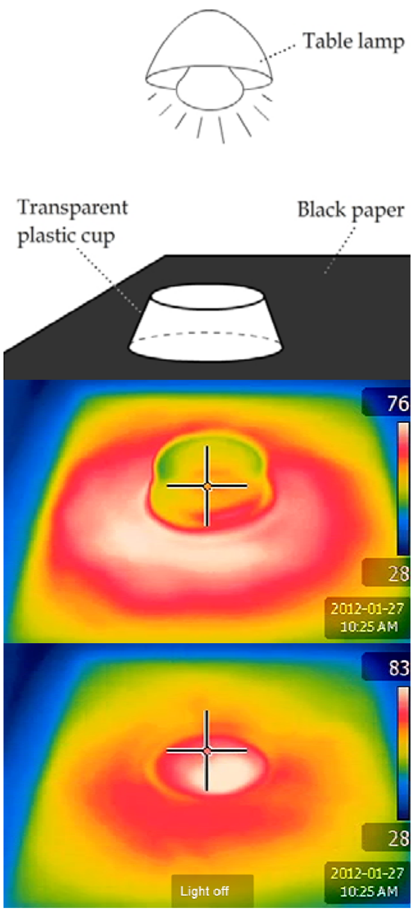


Figure 15: Visualizing the green house effect.

Why is a green house warmer?

This last example (Figure 15) is a simple demonstration of the green house effect. The light from a table lamp shined through an inverted, translucent plastic cup and was absorbed by the black paper inside. But since IR radiation emitted from the paper could not travel through the cup, the heat was trapped inside the cup.

FOR THOSE WHO DO NOT HAVE ACCESS TO AN IR CAMERA: WATCH THE IRTUBE

Even though the prices of IR cameras have plummeted, most teachers and students still do not have access to IR cameras or even know the existence of such a powerful tool. For the science education community to have a fair introduction to what this tool is capable of doing, we have launched the IRTube website (http://energy.concord.org/ir) that disseminates many annotated YouTube videos recorded from our experiments using FLIR's IR Camera Player (currently with a low-cost, low-resolution E30bx thermal camera). Of course, no video on the Web can beat an IR camera in hand! But these videos may still provide invaluable resources to educators. In the YouTube Physics Column, the Physics Teacher Magazine published by the American Association of Physics Teachers recently featured five of our videos and discussed how to use them in the classroom [8].

SUMMARY

The IR experiments described in this paper show that IR imaging has great potential for improving science learning and teaching. Tedious cookbook-style procedures needed to scaffold science experiments, which are common in current science labs in schools, are the likely culprit in taking the excitement and fun away from science. IR imaging represents a new generation of technology that promises to significantly lower the technical barrier to hands-on scientific inquiry. What an IR camera can immediately show and tell would have taken students hours to work out using a thermometer or a sensor. By liberating students from laborious work, an IR camera can directly focus them on science concepts and quickly bring them to high-adventure part of science.

In our limited trials in American and Swedish schools, we have observed extraordinary enthusiasm and interest from students and teachers in this revolutionary visualization tool. We have no doubt that IR cameras have the potential to be an extremely engaging learning tool. Just like microscopes and telescopes, affordable IR cameras should be added to science labs in every school to revolutionize science education.

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ABOUT THE AUTHOR

Charles Xie's passion with IR imaging began in 2010 with a second-hand I5 camera purchased from the Infrared Training Center. To him, an IR camera is a desktop remote sensing system for studying energy flows and transformations—core concepts in almost every subject of science. After being surprised by unexpected thermograms in a few very simple experiments, he quickly realized that IR cameras could one day become an important instrument for learning and teaching science. Since then, he has been working tirelessly to realize this vision.