SEEING THE UNSEEN: AN INVESTIGATION OF HEAT TRANSFER USING INFRARED THERMOGRAPHY AND LABVIEW™

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Seeing the Unseen: An Investigation of Heat Transfer Using Infrared Thermography and LabVIEW™

Abstract

In this thesis work, the capacity of the infrared (IR) camera as a potential tool for creating excitement and engagement among students in the investigation of heat transfer concepts in the classroom is evaluated. Thermal videos of various heat transfer mechanisms captured with an IR camera help students visualize the abstract and invisible heat transfer processes. An interactive program was developed in LabVIEW™ that displays thermal videos captured by an IR camera and allows students to record thermal videos of experiments, plot temperature changes of any point on the thermal video and save their graphical results. To gain insight into the toolkit's ability to generate enthusiasm and engagement among students, preliminary usability testing of the toolkit was conducted with twelve middle school students. Based on oral and written feedback and observed interactions, the toolkit was successful in creating excitement and engagement towards heat transfer among the students. The IR camera, the interactive program and its use by students with emphasis on the advantages of these tools and some of the challenges for their integration in a classroom are discussed.

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1 Introduction

Infrared thermography is an imaging technique, which visually displays the amount of infrared radiation emitted, transmitted and reflected by an object. Thermographic cameras (i.e., IR cameras) are non-contact measurement devices that display temperature distributions of objects or environments based on the amount of infrared radiation they emit. That is, IR cameras capture images of heat (i.e., light invisible to the human eye) rather than visible light.

Figure 1: *Flir® E30bx IR camera used in this thesis work.*

Infrared thermography is a growing field with a wide range of applications. Its use spans from the field of medicine for diagnostic purposes to the evaluation of energy efficiency in the building industry. Over the past twenty years the cost of the IR camera has been steadily decreasing, from $70,000 in the 1980s to under $2000 today [1], which has promoted its expansion into new fields. It is only a matter of time before the IR camera becomes an economically viable educational tool. This thesis presents educational strategies/methodologies in anticipation of the IR camera's introduction into the classroom so that educators and students can take full advantage of this technology as soon as it becomes accessible.

This thesis proposes that the IR camera can become a vehicle through which students learn heat transfer. The IR camera allows students to "see" the invisible phenomena of heat transfer in the form of temperature that occurs in the world around them in real time. These images and videos become the interface through which they access the more abstract relationships and concepts of heat transfer in a program developed in LabVIEW™, which allows students to study and analyze heat transfer processes in real time. For example, students can explore the behavior of temperature over time of an object and/or an environment. With this work, the benefits of the IR camera coupled with the investigational program will hopefully allow students to draw connections between the world around them and heat transfer concepts and creates an engaging environment in which students take charge of their scientific investigations.

2 Literature Review

Over the last couple of decades constructivist learning theory has risen to prominence. Constructivist learning theory poses a fundamentally different account of knowledge than traditional educational models. In constructivist learning theory Hake characterizes students as empty vessels to be filled with knowledge by their teacher. Until recently, the traditional approach has been utilized to impart this knowledge to students. Hake characterizes this traditional approach as "lectures requiring little or no active student involvement, labs with prescribed practical procedures and tests or exams emphasizing quantitative algorithmically solving procedure" [2]. Constructivist learning theory holds that every person understands the world through a set of constructs. Knowledge emerges when new information is either assimilated into an individual's existing constructs, or brings about a restructuring/creation of constructs in order to achieve a coherent view of the world. These constructs are not the same for each individual as they are informed by one's social interactions through her culture and by her experiences. Because constructivist-learning theory proposes a fundamentally different view of knowledge than traditional educational models, it calls for a reconfiguring of the traditional classroom environment in a number of ways. Changes that are specifically relevant to the work of this thesis are addressed.

The constructivist view of knowledge fundamentally changes the teacher's role in the learning process. The teacher is no longer at the center of the learning process, objectively dispensing knowledge to all of her students in the same manner. Because each student has different needs based on her individual constructs, she is the logical center of her learning process. The teacher's role is to assist that process as a facilitator. Ferguson argues that "the trick to teaching is to entice and motivate the students' excitement and interest in the topic, and then to give them the proper tools to reflect, explore, compare, and contrast" [3]. Devices that enable the student to encounter information through first-hand experience, such as an IR camera, allow each individual learner to guide her learning process.

Another key aspect of the constructivist-learning model that is directly related to this thesis is the encouragement of active over passive learning. Active learning describes a process that involves learners in tasks that require analysis, synthesis, and/or evaluation. This process is guided by the learner and designed around tasks that require higher-order thinking such as problem solving, discussion, writing, and debate. In all instances, it is important that students have the opportunity to both question and apply the material they engage. The goal of active learning is to allow students to construct knowledge through the active assimilation of information into their constructs as opposed to the mere reproduction of knowledge that is objectively formulated by a teacher. In one study, introductory physics students who used active learning strategies improved their scores by 48% on the Force Concept Inventory, a standardized physics test that focuses on conceptual understanding, compared to the 23% improvement achieved by lecture-based students [4].The IR camera is an excellent tool for achieving this because it allows students to direct their own investigations.

Another important feature of the constructivist-learning model relevant to this thesis is the preference for situated over detached learning. Detached learning refers to learning that occurs in an environment that does not present a relationship to the material presented. Situated learning describes learning that occurs within a relevant context. Situated learning strategies are most well known in the form of internships, where students learn tasks in the environment in which they will be performed. However, the term has much broader applications, describing learning that occurs in gardens, labs, field trips, and on computers. Situated learning allows students to draw relationships between abstract concepts and real-world activities and scenarios. The IR camera promotes situated learning of heat transfer because it takes as its subject the world around us, allowing students to "see" and analyze temperature in their immediate environments.

The last aspect of the constructivist-learning model relevant to this thesis is its emphasis on the social nature of learning. A student must be given the opportunity to compare her constructs to those of her classmates. Activities that facilitate this comparison are crucial to build into instructional strategies. Strategies that address this issue directly include class discussions and working in groups. However, activities that engage and excite students can have the same effect in a less structured and more organic way. The IR camera allows each individual student to make her own discoveries. These discoveries can later be related to other students' discoveries through class discussion. The range of examples provided by individual investigations can help enrich discussion and comparison.

The use of technology in the classroom, such as an IR camera, can support constructivist instructional strategies in significant ways. A number of studies have shown that classroom social dynamics change dramatically when technology used in the classroom [5, 6]. Technology also has positive effects on classroom interactivity. Classrooms that incorporate computer technology exhibit "a greater amount of teacher interaction with small groups and individual students, student collaboration and cooperation, students' teaching the teacher and one another, and students better regulating their own learning" [7]. With the use of technology, activities that students complete in class can be shared with the entire group. Anderson [8] outlines the benefits of this application of technology:

> It powerfully establishes that the students are direct contributors to the learning environment in the class, which in turn provides an incentive for them to participate and to practice clearly articulating their thoughts in writing. In addition, a diverse set of student responses can help to illustrate different aspects of the same problem, or to present alternative solutions. Finally, the ability to show incorrect solutions and to talk about them without identifying their sources gives the instructor a means to directly and safely address student misconceptions in class.

There is also evidence that suggests technology improves students' attitudes toward learning. Some evidence has accumulated that "innovative technology use in the classroom can have positive effects on student motivation, as well as student self-esteem and classroom behavior (e.g., attendance and time-on-task)" [9, 6]. Finally, J. Kulik [10] provides evidence that the use of technology in the classroom improves student performance; "students who received computer-based instruction (CBI) scored higher and progressed faster over the school year (roughly 3 months on a grade equivalent scale) than students receiving traditional instruction."

In particular, the use of technology in the classroom as a visualization tool is invaluable, especially in teaching science. According to Barak et al., Gilbert, and Zhang et al. "visual representations such as molecular models, simulations, and animations in instructional contexts may afford students with opportunities to promote their understanding of unobserved phenomena in science" [11]. In addition to helping students visualize unobservable phenomena, visual aids also enhance students' conceptual understanding and spatial ability [12, 13], they can also facilitate the processing of complex data, make the scientific process more dynamic, and provide ways for studying interesting and complex phenomena [14]. Finally, technology as a visualization tool is particularly effective in teaching dynamic processes. Garcia et al. and Hoffler and Leutner suggest that an effective method for "teaching dynamic processes is through the use of computerized animation" [11]. Studies show that the use of animations contributes to students' conceptual understanding and motivation to learn science [14, 15, 16].

The use of technology to help students visualize heat transfer is already being researched. Charles Xie at Concord Consortium has developed an open-source program called Energy2D that offers students pre-loaded simulations of heat transfer as well as the ability to create their own simulations. He has also begun to explore the potential for the IR camera to be used as a teaching tool in the classroom through the development of a set of experiments designed to clearly reveal heat transfer processes to the IR camera [17]. Cabello et al. has developed a set of experiments that uncover the processes of heat transfer to university level students using the IR camera. This set of experiments was incorporated into the students' laboratory work. Cabello et al. observed that students participating in the lab were able to "assimilate concepts once they [were] able to interpret the thermal patterns" and were eager "to go further when allowed to discover any heat transfer phenomena themselves" [18].

3 Scope of Work

In this thesis the IR camera, a technology that allows for visualization of heat transfer dynamic processes, is used to create a constructivist learning environment that promotes active learning.This thesis aims to provide a toolkit that allows thermal images taken with an IR camera to be the primary vehicle through which students, grades 6-8, learn heat transfer. With this toolkit, students can take thermal videos of their immediate environment. These videos can be connected to a laptop to generate a live video stream in LabVIEW™. Students can interact with the video stream to access both qualitative and quantitative information about the heat transfers phenomena observed. Finally, each student's individual experiments can be saved or exported to share with the larger group.

The rest of this thesis is organized as follows. The next section introduces the IR camera and briefly illustrated its power as a tool for revealing the processes of heat transfer to students. Then the advantages and disadvantages of the IR camera are compared to two existing tools used for teaching heat transfer in the classroom. The toolkit which we have developed around the IR camera is then introduced. This includes a set of introductory experiments that clearly reveal the processes of heat transfer using the IR camera and an interactive software program developed in LabVIEW™ that allows students to analyze temperature change by interacting with a thermal video. The toolkit was tested by students in grades six and seven and the analysis of the findings of this preliminary test are discussed. Finally, this thesis closes with a discussion highlighting the advantages and disadvantage of the IR technology for use in the classroom and suggestions for future work.

4 IR in the Classroom

The IR camera allows students to explore heat transfer phenomena in the environments in which they occur and in real-time. By simply pointing and shooting, students with limited understanding of heat transfer can reveal these processes as they occur and be at the center of their own learning process. Furthermore, the portability of the IR camera allows students can conduct experiments in the field. This is an example of situated learning, as a direct connection is drawn between the processes of heat transfer and the environments in which they occur. Students are free to explore anything they encounter. An investigation can begin with so little as a question.

4.1 How to Introduce the IR Camera into the Classroom

So how can students and teachers use an IR camera in a classroom? To follow are several examples that can be used to start conversation in the classroom. Figure 2 shows how fur and hair insulate a dog in a cold house, an example of heat transfer due to radiation. One can see the substantial heat loss around the eyes and mouth due to the small amount of hair and fur surrounding these areas but excellent heat retention in the surrounding sections of the body as a result of thicker amounts of hair and fur. Another interesting aspect of this image is the clear identification that the coldest part of a dog's body is the nose, which is a result of both evaporative cooling caused by the dog licking its nose and fluids secreted inside the nose used to regulate its body temperature.

Figure 2: *An IR portrait of a dogs face shows several concepts of heat transfer at work*

Another example that is easy to use in the classroom invloves examining changes in IR images with time for dynamic processes. The series of images in Figure 3 show a very familiar process, the heating of a coffee cup by a hot liquid. Hot water is added to the coffee cup in the upper left image and continues until the cup is full in the lower left image. Both conduction and convection are illustrated in the figure shown below.

As the hot liquid makes contact with the inner walls of the cup, thermal energy from the liquid is conducted to the outer wall of the cup. The cup and the liquid it contains will eventually cool as a result of losing thermal energy to the surrounding air via convection and to the table through conduction. The warmer liquid rises to the top and cools and as a result, increases in density,

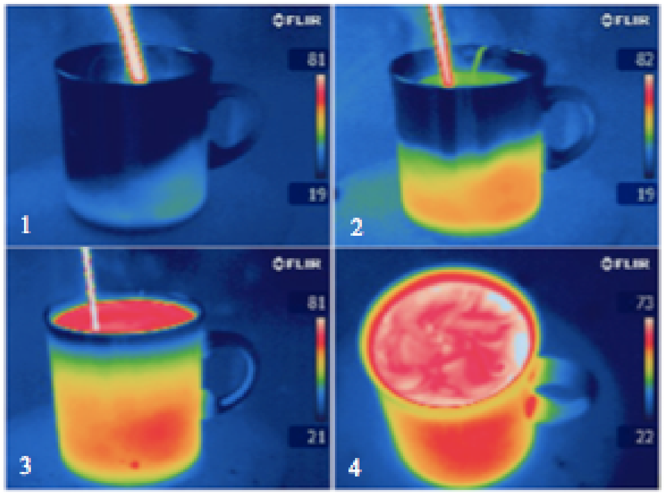


Figure 3: *Series of screenshots from IR video showing thermal conduction between hot water and a coffee cup*

which causes the liquid to sink to the bottom where it begins to warm and the process starts over. The movement of the liquid in this process is captured in the last image. Common activities, similar to the one described, can lead to discussion about heat flux, temperature and material properties and encourage students to explore the effects these factors have on the outcome.

A powerful example to engage students is to investigate indirect effects such as residual heat sometimes referred to as "thermal shadows" [4]. For example, based on residual heat, one can look at an empty couch and determine the number of people previously sitting on the couch and roughly how long they were sitting there. Another simple example of residual heat is when a person walks across a floor while barefoot or wearing socks as shown in Figure 4. Thermal shadows in the form of a footprint appear in the places where a foot touched the floor as a result of conductive energy transfer between the foot and the floor. Using an IR camera, students can continue to watch as the floor cools and the footprints disappear and estimate the thermal conductivity of the floor.

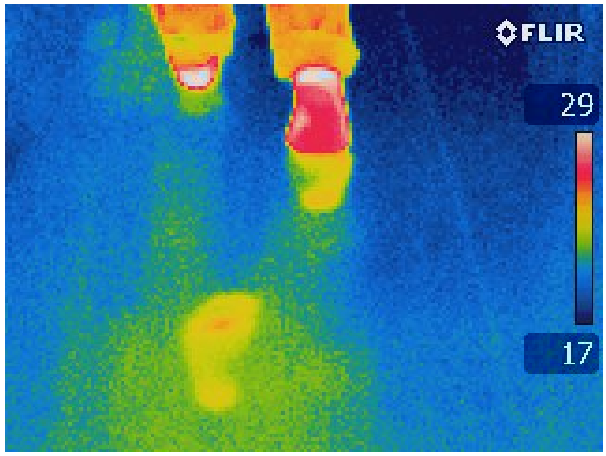


Figure 4: *IR image showing thermal shadows of footprints on a floor resulting from conduction from contact between the foot and floor*

The real power of the camera in the classroom, however, is the fact that it can spark discussion and argumentation. All students have developed various conceptual models related to temperature and heat transfer. The IR camera will challenge some of these models and reinforce others. Through this continual self-validation of their own conceptions, the students will start to understand phenomena they observe and gain a deeper understanding of both the science content (temperature and heat transfer) and the inquiry skills (modeling and validation).

5 Tools for Teaching Heat Transfer

The invisible and abstract nature of heat transfer can make the processes of conduction, convection and radiation difficult for students to grasp. Various methods have been developed with the intent to help students visualize these processes and/or directly link them to the students experiences. To better understand the strengths and limitations of the IR camera, it is helpful to compare its use in the classroom to two other tools used in the teaching of heat transfer: thermometers and simulation.

5.1 Tools Used in the Classroom

A widely used method for teaching heat transfer in the classroom is a hands-on approach using thermometers. With this method students can design experiments and track temperature change over time by attaching thermometers to the objects they are investigating. In order to visualize this data, students can use the measurements collected to make graph after completing experiment or can use thermometers (e.g., Vernier® temperature sensors) in conjunction with a software program (e.g., Logger Lite®) to record and plot the data as the experiment is being conducted.

Another method used for teaching heat transfer is simulation. An excellent example of the way simulation software can be adapted for use in the classroom is provided by Energy2D. Energy2D [19] is a free, user-friendly, interactive software program accessed online that helps students visualize heat transfer processes. Students can explore pre-loaded simulations that illustrate the three basic heat transfer mechanisms, Figure 5, as well as a broad range of applications such as building energy analysis, heat and mass transfer, and earth science. For these simulations users simply run the chosen application using the controls located at the bottom of the user-interface (see Figure 5) however long they wish. Users can also discover the parameters behind the heat transfer visualizations by accessing the properties dialogue box as shown in Figure 6. The parameters defined in this box describe the geometry, heat source, thermal properties, and optical properties.

Users can also create their own simulations, see Figure 7. In order to do so, a user must draw a 2D representation of the objects they wish to investigate, defining both the basic geometry of the objects and the distances between

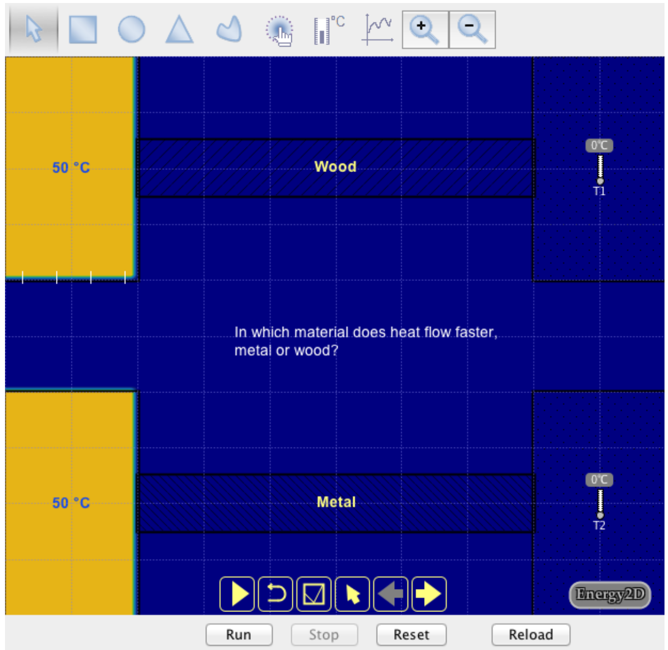


Figure 5: *Example of pre-loaded conduction simulation in Energy2D*

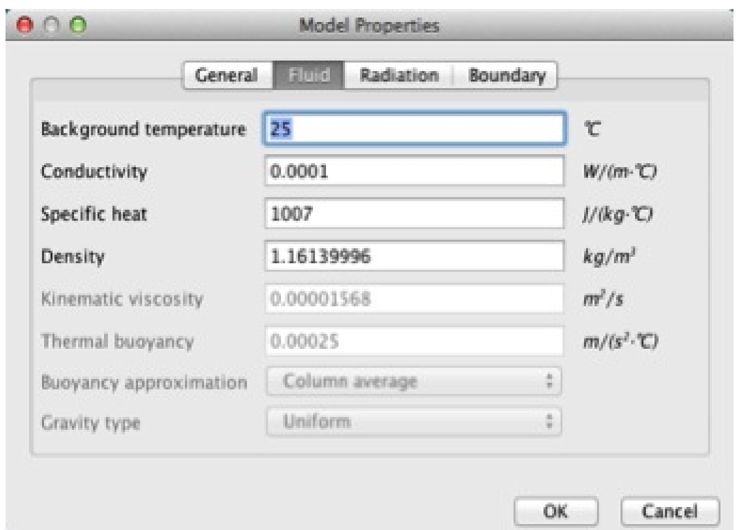


Figure 6: *Energy2D property editor dialog box*

them. This can be done using the tools in the toolbar, which is located at the top of the user-interface, see Figure 5. Then users must input the relevant thermal and optical values of the objects. For example, if the simulation depicts the flow of energy from a coffee cup to a glass table, the user would need to determine the thermal and optical properties of the cup and the table in order to produce accurate results.

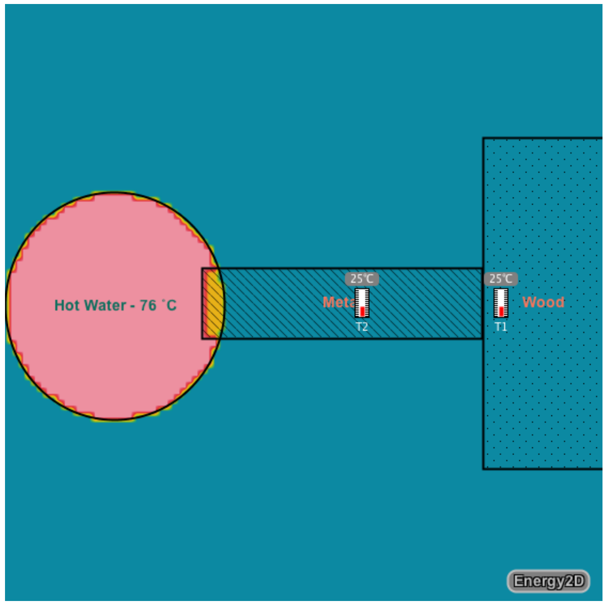


Figure 7: *Example of user-defined conduction simulation in Energy2D*

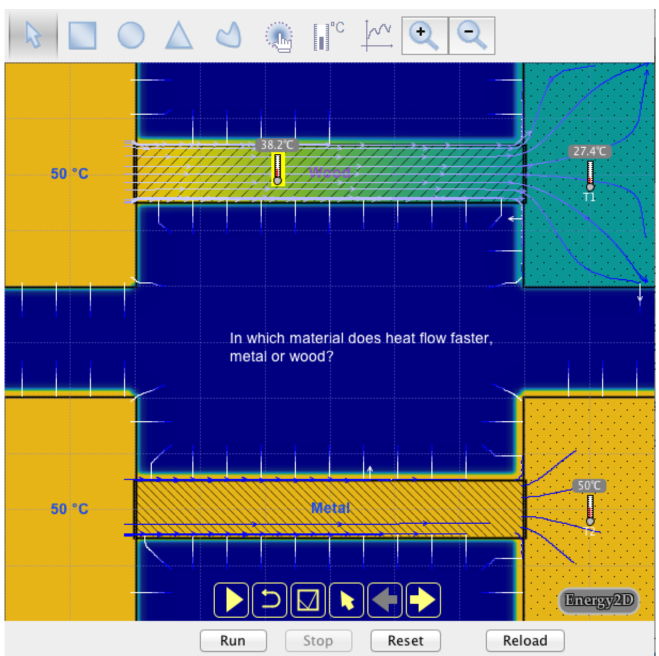


Figure 8: *Users can add a thermometer to display the temperature of a specific location within the model*

In both the pre-loaded and user-defined simulations, quantitative information is provided in addition to visual representations. Users can output the temperature of specific locations by inserting a virtual thermometer at a point within the model, see highlighted thermometer in Figure 8. Moreover, users can display a graph to be used for further analysis as shown in Figure 9 that plots the temperature changes of the virtual thermometers in the model.

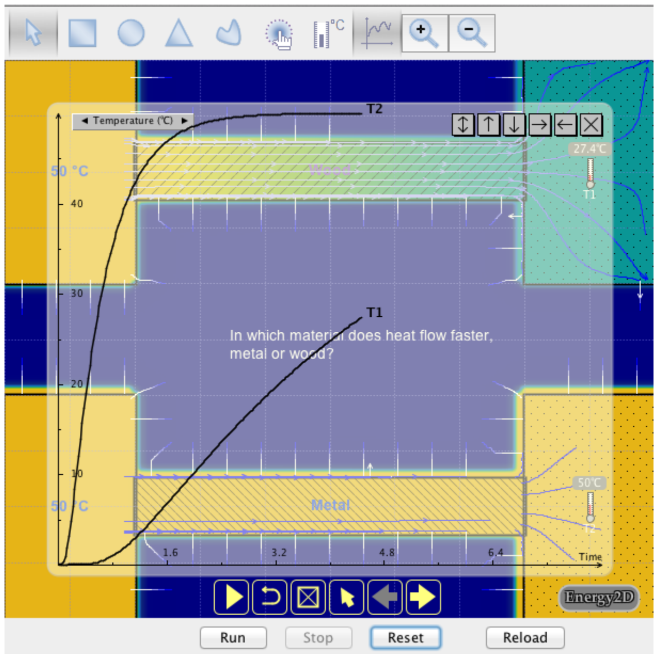


Figure 9: *Users can turn on a graph that displays the change in temperature for each thermometer located within the model*

5.2 Comparitive Analysis of the Tools

In this section, the strengths and weaknesses of the IR camera, thermometers and simulations are presented. The three tools will be disscussed in terms of accessibility, user interface, strength of visualization, and the directness of its relationship to the phenomena studied.

Widely accessible tools include both the thermometer and Energy2D simulations. Thermometers are common and affordable, making it possible to have many in a single class. Energy2D is a free software program that can be accessed online, or downloaded to a users for access offline. Its use in the classroom is limited only by the number of available computers. The IR camera is currently too expensive to be used as a teaching device in the classroom. However, it is likely that within the next five to ten years, the device will be accessible to teachers who wish to use the camera in group assignments.

The thermometer provides a straightforward user interface. The user must simply attach the thermometer to the object he is studying and track changes in temperature over time. Energy2D presents a very intuitive interface for its simulations. The pre-loaded simulations can be viewed by users with very little understanding of heat transfer. Though the user-defined experiments benefit from the same easy to use interface as the pre-loaded simulations, the ability to produce a thermal simulation is limited to more sophisticated users who can accurately model the environment studied by inputting its thermal properties. To get a better understanding of Energy2D, see Appendix D, which explores Energy2D through the presentation of three user-defined simulations. With minimal instruction, users of the IR camera can create thermal videos of heat transfer phenomena. They are as simple to use as a point-and-shoot camera. Users need only be able to determine the atmospheric temperature, the distance from the object they are studying, reflected temperature, relative humidity and its emissivity. Most of these parameters can be determined using a thermometer and the IR camera. Thus, a user with very little understanding of heat transfer can produce high-quality thermal videos.

The thermometer is limited in its ability to provide a visualization of heat transfer. At best, thermometers can be connected to software that creates a graph of temperature change over time and can quickly measure temperature change with time, but thermometers are not able to provide an instananeous spatial map of temperature. Energy 2D provides excellent visualizations of heat transfer in a 2D environment. Students can see both a color mapping of temperature on the objects they are studying and quantitative graphs of temperature change over time. As a visualization tool, Energy 2D is effective for simplified cases given the difficulty of mapping complex environments in two dimensions. Whereas, the IR camera is an excellent tool for visualizing heat transfer, as it provides three-dimensional images and videos of complex thermal environments in real time.

Finally, the three devices present vary different relationships to the environments being studied. As a simulation software, Energy 2D does not present a necessary relationship between the phenomena studied and the environment in which it occurs. The thermometer is great for situated learning because the students measure the temperature change of the objects in which they study directly. The thermometer is also easily portable, meaning students are not limited to experiments in the classroom, but can test heat transfer phenomena in the environments in the field. The IR camera, is also portable and provides an excellent visualization of heat transfer phenomena in the field. Thus, it is a very powerful tool for situated learning, as it provides both qualitative and quantitative heat transfer information with a direct relationship to the envirnoment being studied.

6 The IR Camera and LabVIEW™

The IR camera as a stand-alone device is already a powerful tool for learning heat transfer within the constructivist learning model because it encourages both student-led investigations and situated learning. In order to more fully harness the potential of heat transfer imaging in the classroom, development of a complimentary program was necessary. This toolkit allows students to become the centers of their learning process and to directly relate representations of heat transfer to their experiences of these phenomena in the environments in which they occur and in real time. Furthermore, this toolkit allows students to easily share their discoveries with their classmates providing a basis for discussion and further inquiry. This thesis proposes that thermal information from the IR camera can be streamed into LabVIEW™ in order to output both quantitative and qualitative information about the heat transfer images.

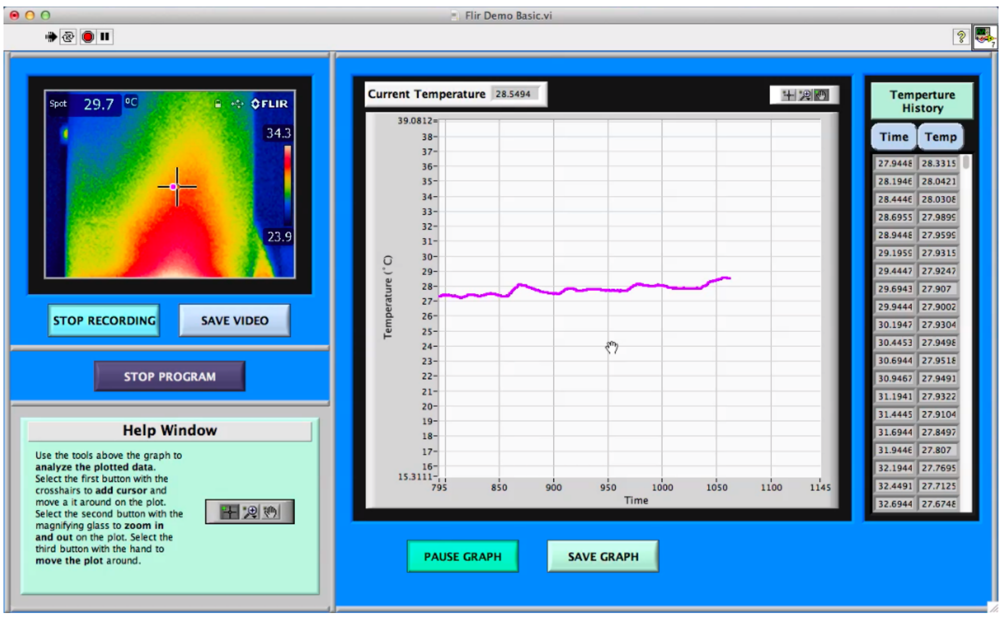


Figure 10: *User interface of the toolkit software program*

By connecting the IR camera to a computer, users can stream a live feed of the thermal video captured by IR camera into LabVIEW™, Figure 10 and can record and save an IR video. This allows users to record a movie of an experiment which they can revisit at a later time for reference and/or further analysis. Moreover, users can select any point on the infrared image displayed in LabVIEW™ to create a graph that plots the temperature values of that point over time. The graph is displayed beside the thermal image so that students can compare the abstract pattern of temperature change depicted on the graph to the thermal image. Users can interact with the graph in several ways. They can select a specific point on the graph to read exact values at that point. They can also zoom into specific areas of the graph, which is particularly helpful for data collected over long periods of time. Finally, users can pause and save the graph as needed.

A key goal of the development of the LabVIEW™ application is to allow users to share their individual investigations with others. This is a key aspect of the constructivist learning model, which recognizes the social nature of learning to be critical. In LabVIEW™, students can save recordings of both the thermal video and the complimentary graph. These videos allow a student to compare one experiment to another, as well as to see the effect of minor changes in the same experiment. For instance, how does a piece of wood conduct heat from a heat source compared to a piece of metal of the same size? The toolkit also allows students to share their diverse experiments with the larger group. Teachers can use these videos to illustrate important themes shared between experiences. The students involvement in producing the material that is the basis for the class discussion will encourage their interest in the discussion.

6.1 The LabVIEW™ Program

The software portion of the toolkit was developed using LabVIEW™. Figure 11 shows main Virtual Instrument (VI) (i.e., the high-level code) used to run the program. Once the Run button is clicked, the code execution begins by grabbing the video from the IR camera and displaying the raw image in the user interface in real time, see Figure 10. Next, the image is converted to grayscale, and the minimum and maximum temperatures are determined by by a sub-VI (i.e., a program within the main program). In this sub-VI, images of the minimum and maximum temperatures are recorded from the IR camera, illustrated in Figure 12. At this point LabVEIW™ is not able to output the numbers captured from the IR camera.

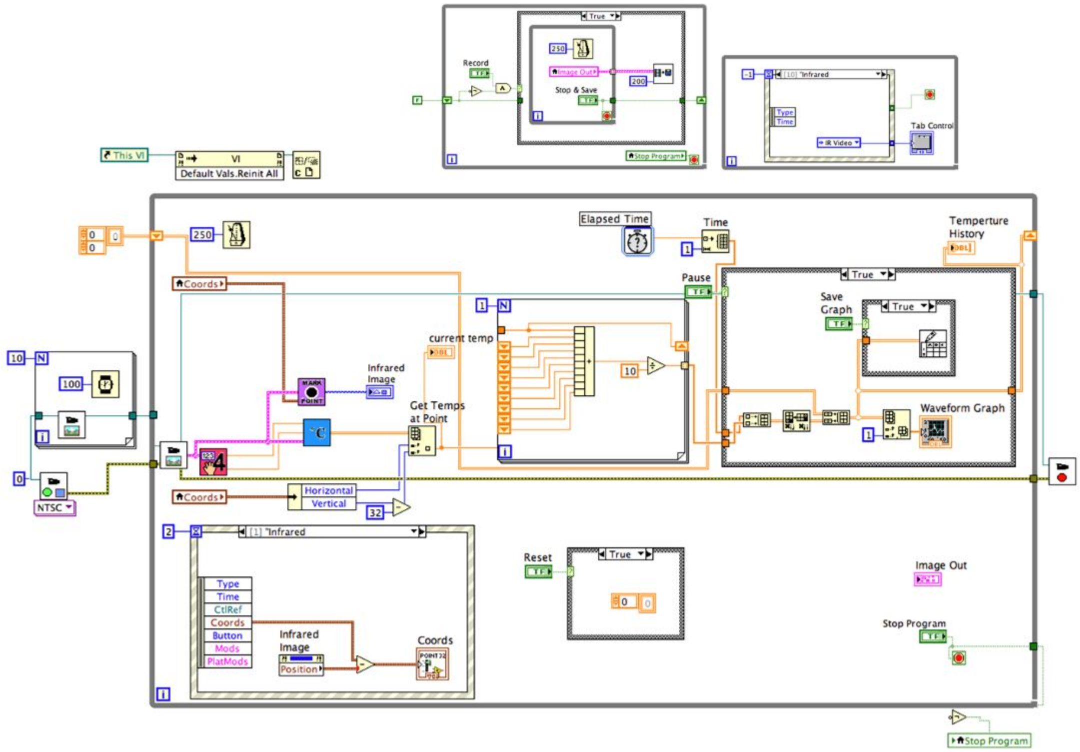


Figure 11: *High-level code (i.e., main VI) of the toolkit software*

Further image acquisition techniques are utilized to determine each digit in the image in another sub-VI. The temperature range is then divided by 255 to create a linear temperature distribution, which creates a temperature map of the image. Once the user turns on the graph, a moving average of the temperature of the point selected on the IR image is plotted. The moving average is a type of low-pass filter used to reduce noise in the data. All of the steps just described occur every 0.25 seconds allowing the data to be collected and examined in real time.

The other features controled by the main VI include the help window, which displays text explaining what how to use each feature when the user hovers over it, the ability for users to record and save a video and/or the graph. The code in Figure 11 is not representative of all of the code developed to run the

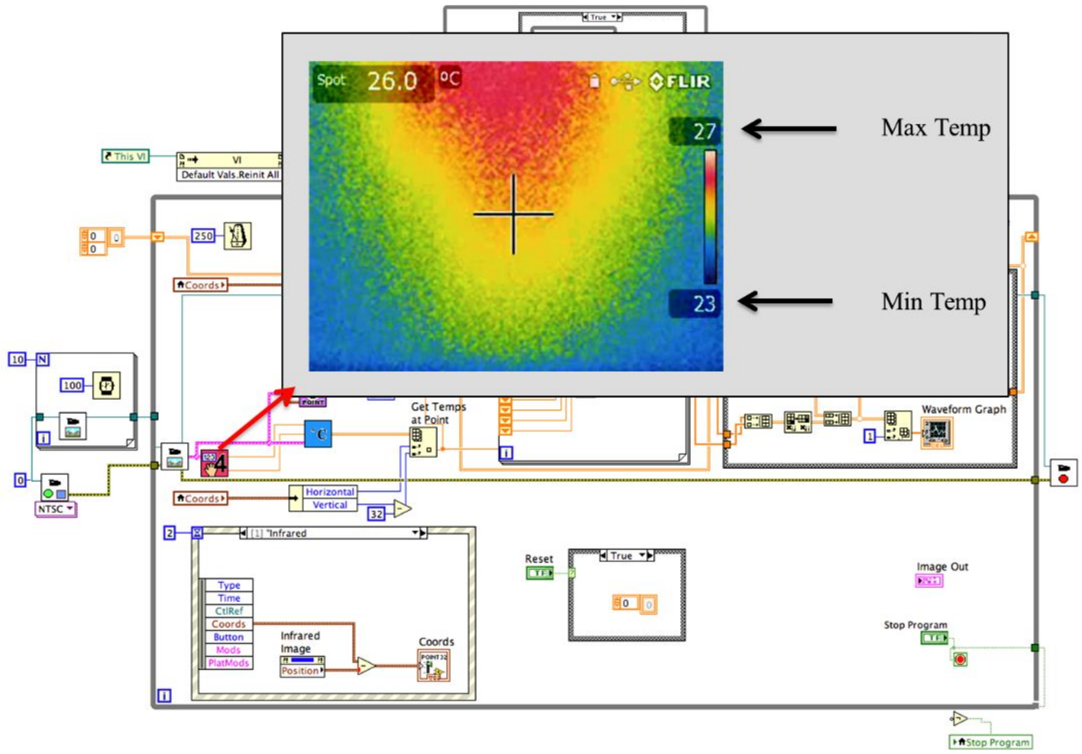


Figure 12: *Illustration of how the temperature sub-VI works*

program. There are a number of sub-VIs, which contain sub-VIs of their own. That said, this code is quite extensive and a description of the entire program is beyond the scope of this thesis.

6.2 Experiments for the Classroom

The following experiments were designed as introductory exercises that clearly reveal the mechanisms of heat transfer using an IR camera. They are intended as a starting point from which students can move on to designing their own experiments. Three experiments, one covering each of the main modes of heat transfer, are presented. The experiments are based on simulations from Energy2D and IR research conducted by Charles Xie and colleagues [17]. A long wave (7.5-13 μm) Flir® E30bx camera was used to examine the three modes of heat transfer: conduction, convection and radiation. The E30bx contains a 160 x 120 pixel detector and is accurate to within 0.1 °C [5], which is sufficient for the purposes of this research.

6.2.1 Conduction

A simple experiment, similar to those just mentioned, that allows an IR camera to capture heat flux in an aluminum bar was developed for students to "see" thermal conduction.

The set up consists of a block of yellow pine wood, a 6061 aluminum bar (spray painted white to increase its emissivity), a coffee cup, a coffee cup warmer, fabric and a Styrofoam cooler. Place the coffee cup on the cup warmer and the block of wood to the right of the cup so that both are at the same height. Place the aluminum bar on top of the cup and wood block so that enough of the bar is suspended over the inside of the cup. Figure 13 below shows a schematic of the experimental setup. Position the IR camera above and perpendicular to the experimental setup in the cooler. Adjust the emissivity, atmospheric temperature, relative humidity, distance and reflected temperature settings on the IR camera to ensure accurate temperature readings before beginning the experiment. For this particular setup the following values[1] were inputted into the IR camera: emissivity = 0.98 (flat white paint), atmospheric temperature = 25 °C, relative humidity = 50%, distance = 0 m and reflected temperature = 23 °C.

Turn on the cup warmer and place the fabric over the top of the cooler and camera to minimize energy loss to convection. After the cooler and the objects inside reach an equilibrium temperature of 25 °C, water is heated in an electric kettle and added to the coffee cup via a funnel. The cup must be

[1]See Appendix E for a description of how to determine and set these parameters in the IR camera.

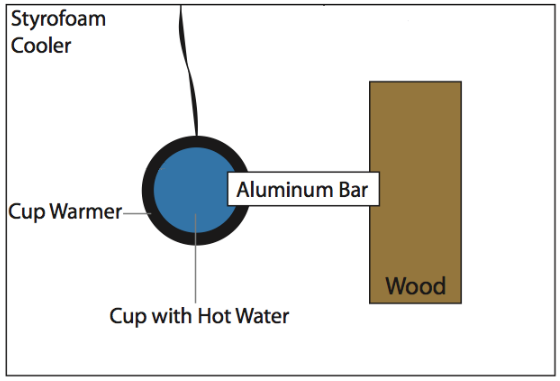


Figure 13: *Experimental setup for conduction experiment*

filled to the very top so that the bottom of the aluminum bar and hot water are in contact.

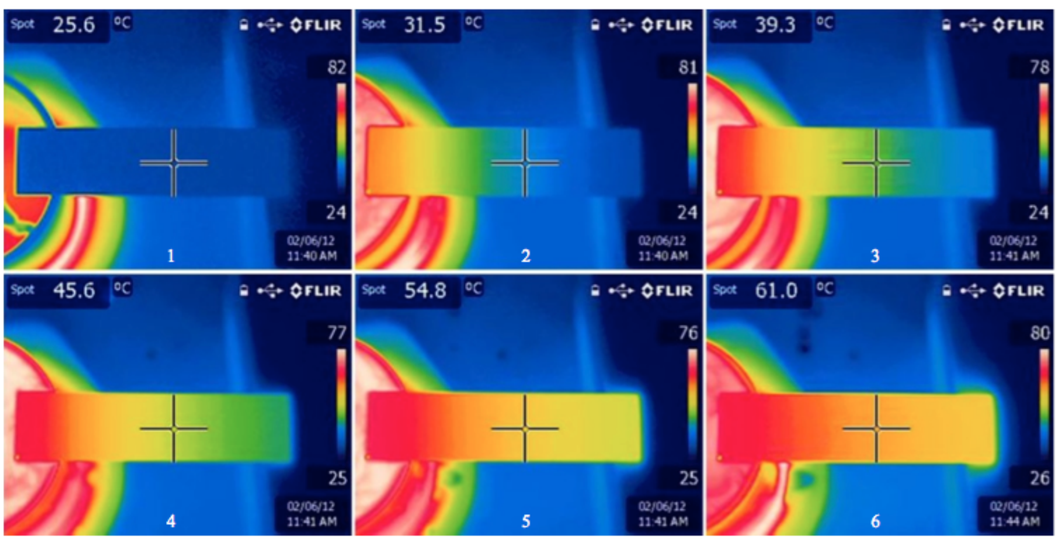


Figure 14: *Series of screenshots from an infrared video capturing conduction through an aluminum bar in real time*

Results of the experiment are shown in Figure 14. The IR camera clearly reveals the uniform transfer of thermal energy through the aluminum bar via conduction. Later in the experiment the IR camera captures thermal energy being transferred from the bar to the wood via conduction in image six. For this experiment, the water in the cup was initially at 78 °C when conduction in the bar began. The position of the bar marked by the crosshair reached

61 °C after three and a half minutes. In this time the temperature of the water decreased by approximately 2 °C and the surrounding air temperature increased by approximately 1 °C.

6.2.2 Convection

A simple experiment that uses an IR camera to uncover convective heat transfer is described in this section.

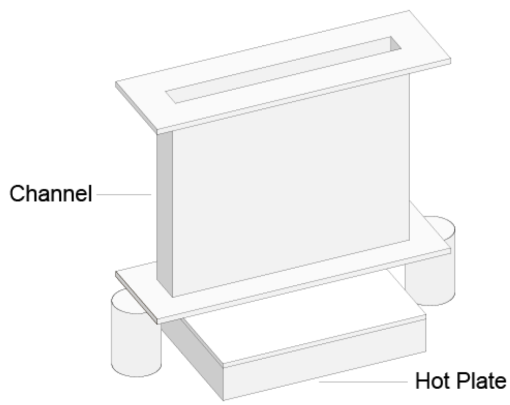


Figure 15: *Experimental setup for natural convection*

The setup consists of a channel constructed of foam core suspended above a hot plate. The channel can be suspended over the hot plate using objects that are readily available. Two jars, one on either side of the hot plate, are used in this setup to suspend the channel over the hot plate. Figure 15 shows a schematic of the experimental setup. A hot plate provides a constant source of energy across the entire opening of the channel. Note, that a light bulb covered with aluminum foi[2] l can be used if a hot plate is not available. Position the IR camera perpendicular to the surface of the channel and adjust the emissivity, atmospheric temperature, relative humidity, distance and reflected

[2]Covering the lightbulb with aluminum foil inhibits the transfer of thermal energy via radiation from the lightbulb, and thus the IR camera from "seeing" the lightbulb's high temperature allowing the user to focus on convective heat transfer

temperature settings on the IR camera to ensure accurate temperature readings before beginning the experiment. For this particular setup the following values[3] were inputted into the IR camera: emissivity = 0.90 (white foam core), atmospheric temperature = 25 °C, relative humidity = 50%, distance = 0 m and reflected temperature = 24 °C.

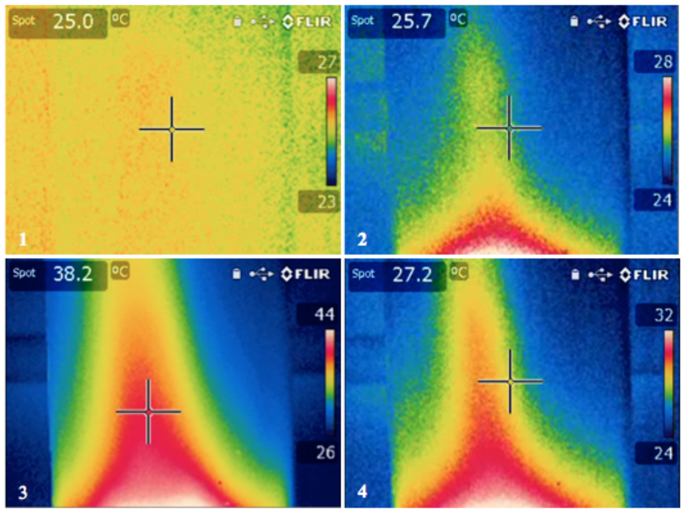


Figure 16: *Series of screenshots taken from an IR video showing convection through an open channel*

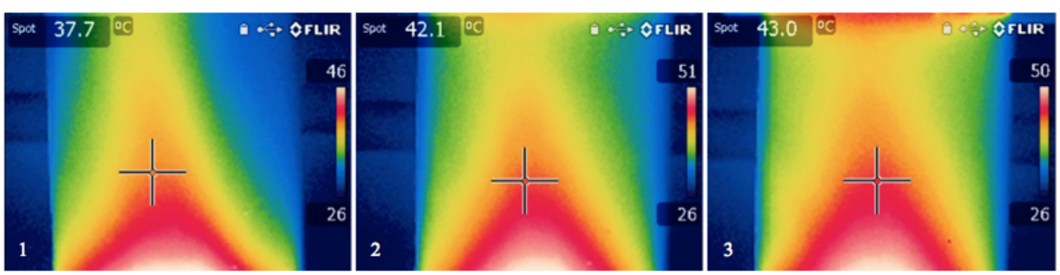


Figure 17: *Series of screenshots taken from an IR video showing natural convection in a covered channel*

While the channel is at room temperature, turn the hot plate on to 100 °C. Shortly after, a temperature gradient should begin to form on the channel wall, shown in image two of Figure 16. This gradient is a result of the air

[3]See Appendix E for a description of how to determine and set these parameters in the IR camera.

warmed by the hot plate transferring thermal energy to the cool surrounding air as it rises via convection.

A cover can be placed on top of the channel to represent the effects of a ceiling in a building, see Figure 17. Thermal energy is transported in the same process previously described, but the cover causes a buildup of the warmed air at the top of the channel.

6.2.3 Radiation

In this section a simple experiment that uses the IR camera to expose thermal radiation is described.

The materials needed for the experiment include a sheet of paper, which will act as a screen, a mason jar, hot and cold water, a ruler and tape. To set up the experiment, the sheet of paper is fixed in an upright position so that the bottom of the paper is touching the table. Objects in the room, such as books, can be secured to the two short edges of the paper using tape. The majority of the backside of the screen should be unobstructed. For consistency place a piece of tape 10 cm from the back of the screen. The IR camera should be set up perpendicular to the side of the screen without the tape and adjust the emissivity, atmospheric temperature, relative humidity, distance and reflected temperature settings on the IR camera to ensure accurate temperature readings before beginning the experiment. Figure 18 shows a schematic view of the experimental setup. For this particular setup the following values[4] were inputted into the IR camera: emissivity = 0.90 (white paper), atmospheric temperature = 25 °C, relative humidity = 50%, distance = 0 m and reflected temperature = 24 °C.

[4]See Appendix E for a description of how to determine and set these parameters in the IR camera.

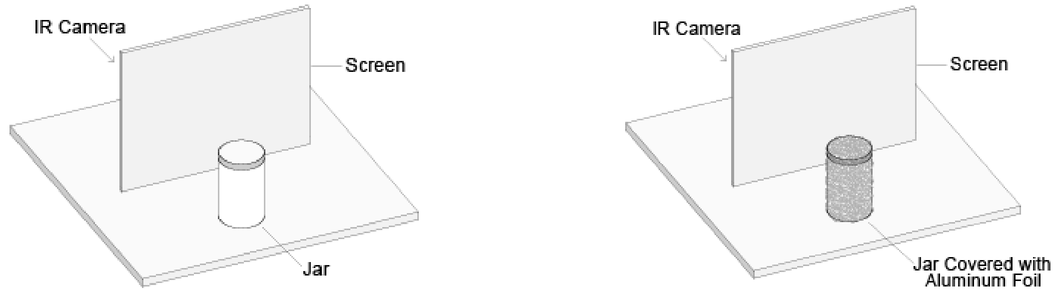


Figure 18: *Experimental setup for radiation - jar without aluminum foil (left) and with aluminum foil (right)*

Place a sealed[5] jar containing hot water, 91 °C, on the piece of tape. Results similar to those in Figure 19 should occur. The first image shows the screen at room temperature without the jar behind it. The second through the sixth images illustrate the development of a temperature gradient on the screen which increases with time as a result of energy transfer in the form of radiation. The thermal radiation emitted from the jar can be captured because as it reaches the screen, the thermal energy is quickly conducted to the front of the screen because it is very thin. Note that if the jar is placed too close to the screen convection may interfere and undesirable results may occur.

Next, allow the screen to return to room temperature and place a sealed jar containing cold water on the piece of tape. A pattern similar to that in Figure 20 should appear. The cold water causes a temperature gradient on the screen that decreases with time because the piece of paper is emitting more radiation than the jar. This is the same effect a person standing in front of an open refrigerator experiences. Images 2 through 4 in Figure 20 show the temperature of the screen decreasing after the jar of cold water is introduced, and increasing to its initial temperature after the jar is removed, shown in images 5 and 6. In this experiment cold water at 0.1 °C was used to achieve

[5]Sealing the jar helps reduce convection between the hot water and air, thus increasing the time it takes the hot water to cool. It also aids in prevention of spills.

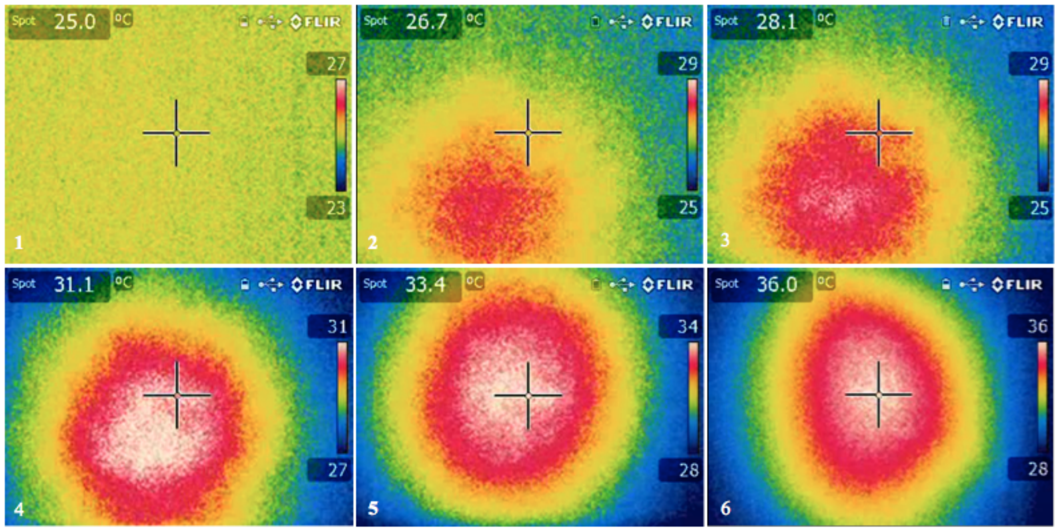


Figure 19: *Series of screenshots taken from an IR video showing an increase in screen temperature due to radiation from a jar filled with hot water*

clear results in a short amount of time.

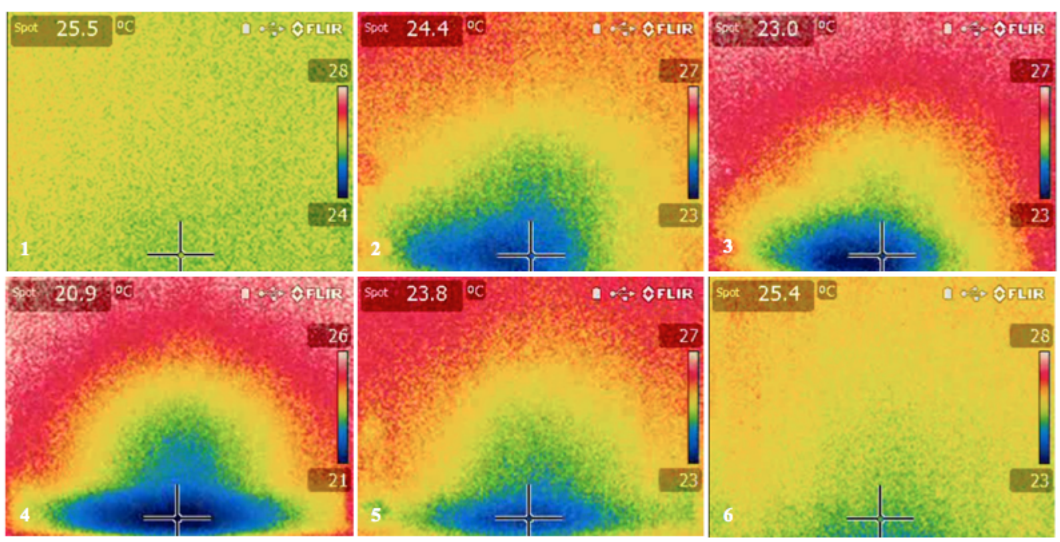
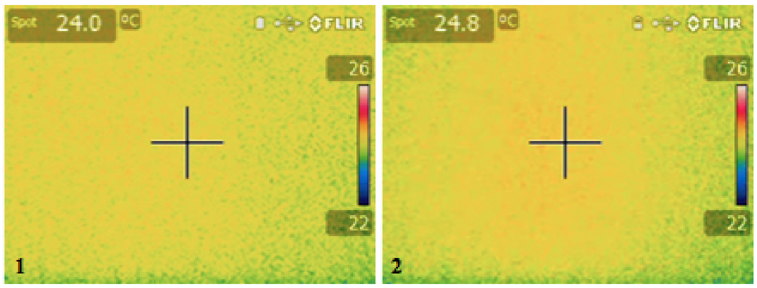
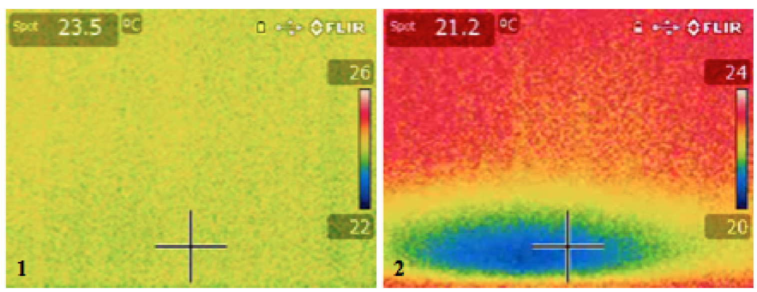


Figure 20: *Series of screenshots taken from an IR video showing a decrease in screen temperature due to radiation from a jar filled with cold water*

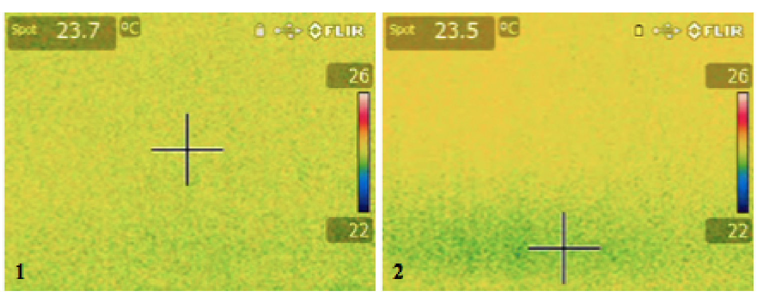
Wrapping the jar in aluminum foil further reveals the effects of thermal radiation. Wrap the sealed jars containing hot and cold water in aluminum foil. Take turns placing the covered jars on the piece of tape making sure to leave time in between for the screen to return to room temperature. The aluminum foil acts as a shield, preventing the transfer of thermal energy via radiation. Figure 21a and Figure 21c show the effects of the aluminum foil. There is little to no change in the screen temperature from the hot and cold jars verifying that the aluminum foil was successful in preventing radiative heat transfer from the jar. Notably, a very small increase in temperature appears in Figure 21c as a result of the reaction of radiation emitted by nearby objects from the foil to the screen.



(a) Image 1 shows initial equilibrium state and image 2 shows effect of jar with water temperature of 91 °C covered with foil



(b) Image 1 shows initial equilibrium state and image 2 shows effect of jar with water temperature of 0.1 °C covered with foil



(c) Image 1 shows initial equilibrium state and image 2 shows effect of jar with water temperature of 11.4 °C covered with foil

Figure 21: *Screenshots from IR video showing effects of aluminum foil on radiative heat transfer.*

The experiments involving freezing water produced an intriguing "UFO" pattern on the screen, Figure 20. Although the cause of this result is not yet understood, one possible explanation is that thermal energy is reaching the screen in the form of convection due to the development of condensation on the table as a result of the near freezing temperature of the water contained within the jar. The bottom part of the ufo pattern appears even when the jar is covered with aluminum foil in Figure 21b; however, when the temperature of the water was increased to 11.4 °C, this pattern no longer existed as shown in Figure 21c. This suggests that the distance between the jar and the screen is not large enough to prevent thermal energy as a result of convection or condensation from the freezing liquid and convection must be considered.

There are many aspects of heat transfer at play here that can be studied and discussed in the classroom. Why is the change in temperature of the screen much larger when the jar is filled with hot liquid? Why does the screen return to its initial temperature after the jar is removed faster in the experiment with the cold jar? What effect does the distance between the jar and the screen have on the temperature gradient shown on the screen? These are just a few discussion questions that will prompt students to think critically and investigate further. Additional experiments to explore some of the above questions include placing the jar at varying distances from the screen, changing the temperature of the liquid, using different liquids, placing various objects behind the screen, etcetera. With a few everyday objects, the easy to use IR camera reveals the invisible heat transfer phenomena occurring within them.

6.3 Preliminary Toolkit Testing

To investigate whether the toolkit creates excitement and engagement toward heat transfer concepts in the classroom a study was conducted with six sixth grade and six seventh grade students. The study was conducted at the Center for Engineering Education and Outreach (CEEO) at Tufts University. Four two-hour sessions, each with three participants, were conducted. The same Flir® E30bx camera used to conduct the aforementioned experiments was used in the preliminary toolkit testing.

6.4 Test Setup and Participant Background

Participants were asked to fill out a pre-activity survey at the start of the session to gain insight into factors that may affect the levels of excitement and engagement seen among the individuals as well as the effects of an individual on the group dynamics. The pre-activity survey, developed specifically for this usability test[6], focused on gaining insight into participants' educational backgrounds and understanding of heat transfer, asked questions concerning participants background including their current grade level, if they have ever used an IR camera, if they have ever used LabVIEW™ and if they have been introduced to heat transfer in class.

Of the 12 students that participated in the study, seven were in the sixth grade and five were in the seventh grade. One out of the 12 participants had used an IR camera, while five others said they had either seen or heard of an IR camera. None of the participants had ever used LabVIEW™. Eight out of 12 participants had been introduced to heat transfer in class, while four had not. Appendix A shows a table of the participants backgrounds.

Participants were also asked four questions to determine their level of understanding of heat transfer in general as well as their understanding of conduction, convection and radiation before beginning the activities. Detailed responses to these questions are presented in Appendix B.

[6] The survey was developed in conjunction with two Tufts University, engineering professors (one with significant research experience in K-12 engineering education).

Nine[7] out of 12 (4 sixth graders and 5 seventh graders) participants provided an explanation that demonstrated at least a general understanding[8] of heat transfer. Most participants provided rational along the lines that heat transfer is when heat or energy moves from one object to another. Two out of 12 (2 seventh graders) participants provided an explanation that demonstrated at least a general understanding of conduction stating that heat is transferred in the form of conduction between two objects that are in contact with each other. Four out of 12 (2 sixth graders and 2 seventh graders) participants provided an explanation that demonstrated at least a general understanding of convection saying that convection occurs when a fluid or air rises as a result of being warmed and cool fluid or air moves downward until it is warmed and the cycle resumes. Four out of 12 (1 sixth grader and 3 seventh graders) participants provided an explanation that demonstrated at least a general understanding of radiation. Participants said that radiation originates from objects and can travel through empty space. The responses provided by the participants prior to the start of the activities suggest that the students' exposure to and experience with heat transfer varied.

After completing the pre-activity survey participants were given a brief overview of the three basic heat transfer mechanisms (i.e., conduction, convection and radiation), the IR camera and the LabVIEW™ program. Next, the first experiment investigating conduction was presented. This experiment is described in detail in section 6.1. Participants were asked to make a graph predicting what would happen to the center of an aluminum bar at room temperature after one end comes in contact with near boiling water as a way to gauge their understanding of heat transfer and to get them engaged in the

[7]The remaining participants did not provide an answer or provided an incorrect answer.

[8]Participants demonstrated a general understanding of heat transfer and heat transfer mechanisms if he/she provided a mostly correct description of or example of the associated heat transfer process.

exercise. The participants then started the program and began recording the IR video, Figure 22. Next, they selected the location for which they wanted to plot the temperature (i.e., the center of the bar) and started the graph. Participants watched as the IR camera revealed the temperature change of the bar in colorful images on the screen and tracked these changes in temperature on the graph. With little prompting participants began comparing the graphical results with their predictions.

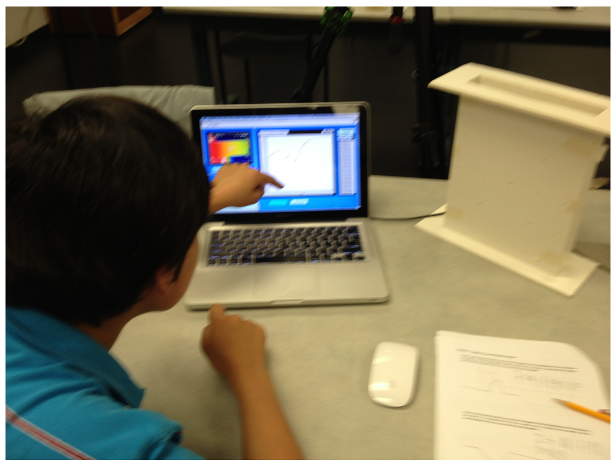


Figure 22: *A participant watches as temperature values of the point selected on the thermal image are plotted*

An experiment investigating convection was conducted next. As in the first activity, the convection experiment discussed in section 6.2 was presented and participants were asked to predict what would happen to the surface temperature of the foam core at the center of the channel. Participants graphed their predictions and started the program. They started recording the video and selected the location of the temperature they wanted to track (i.e., the center of the channel). Participants started the graph and watched as the temperature of their selected location began to increase. With little prompting participants began comparing their graphical prediction with the data being recorded in LabVIEW™.

After completing two of the experiments designed for use with the toolkit, participants were given the opportunity to lead their own heat transfer investigations. A few simple heat transfer concepts including using hands and ice to write on walls, the ability of materials to block or transmit infrared radiation and evaporative cooling were presented to the participants as a prompt for the exploration to begin.

The session concluded with the participants completing post-activity interview questions. Participants were asked various questions about the activities (e.g., what they liked most and least) and the toolkit (e.g., the toolkits ability to help them visualize and understand heat transfer). Participants were also asked to explain heat transfer, conduction, convection and radiation. The post-activity interview questions serve as a measure to determine participants level of engagement and excitement towards heat transfer and the toolkit.

6.5 Test Results and Analysis

With little prompting participants began exploring myriad heat transfer concepts such as heat flux, emissivity, reflectivity, evaporative cooling, thermal shadows and friction. They were particularly intrigued by the ability to write messages on the wall using their hands and ice cubes, Figure 23. Another concept that fascinated participants was the ability materials have to transmit, absorb and reflect radiation. These concepts led their exploration in the direction of invisibility cloaks (i.e., they hid from the IR camera behind a piece of fabric that absorbed IR), Figure 24, IR reflections in aluminum foil and determining the kind of ice cream through wrappers which transmit IR, Figure 25.

Not only did the toolkit create excitement, it also sparked discussion among the students Figures 26 and 27. Suddenly students were asking questions like,

Figure 23: *Thermal image of participant using an ice cube to play Tic Tac Toe on a wall*

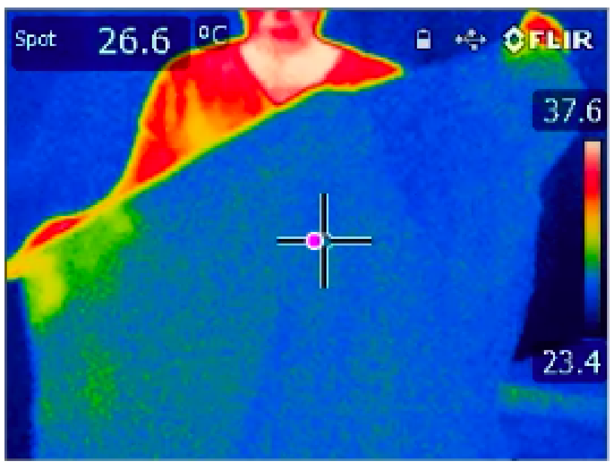


Figure 24: *Thermal image of a participant using a piece of fabric to make himself "invisible" to the IR camera*

“‘I wonder if you could tell the difference between a lemonade ice cube and a regular ice cube [using the IR camera]?’ and ‘If you were using an IR camera on a hot day, would you not be able to see anyone?”’ Instead of the instructor leading the discussion and answering questions, the participants were using the tools to find the answer. One group tested whether or not they could write on a white board using their hands and produce the same effect seen on the wall. One participant used his hand to write a message using friction but was unsuccessful in his first attempt and asked, "What if I push harder?"

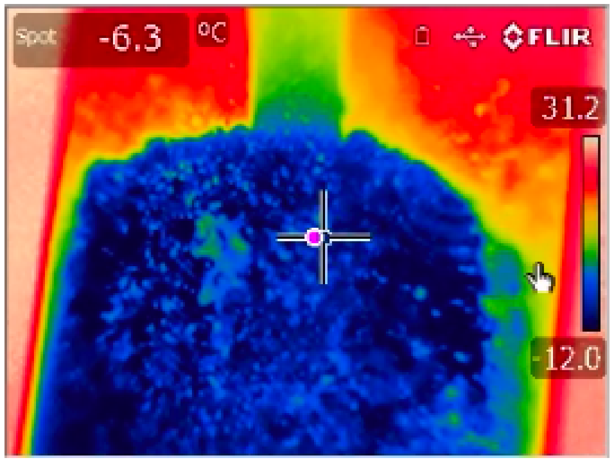


Figure 25: *Thermal image of ice cream bar coated in cookie crumbs while still inside wrapper*

Another participant suggested he use the eraser explaining, "The eraser creates friction, so it makes heat and you can see that." These are just a few examples demonstrating the capability of the IR camera to demystify heat transfer. This was especially true for one participant who said, "[I] didn't know that heat could travel from one thing to the next."

The same questions asking participants to explain heat transfer, conduction, convection and radiation in the pre-activity survey were asked in the post-activity interview question form. These questions were repeated with the hope of gaining insight into the level of student engagement and/or excitement during the activities. An overview of participant responses is provided next. Detailed responses are provided in Appendix C.

Ten out of 12 (5 sixth graders and 5 seventh graders) participants provided an explanation that demonstrates at least a general understanding of heat transfer. Participants explained in one form or another that heat transfer occurs when heat/energy moves/is transferred from one object to another. Eight out of 12 (3 sixth and 5 seventh graders) participants provided an explanation that demonstrates at least a general understanding of conduction noting that conduction is the transfer of heat/energy through a solid or be-

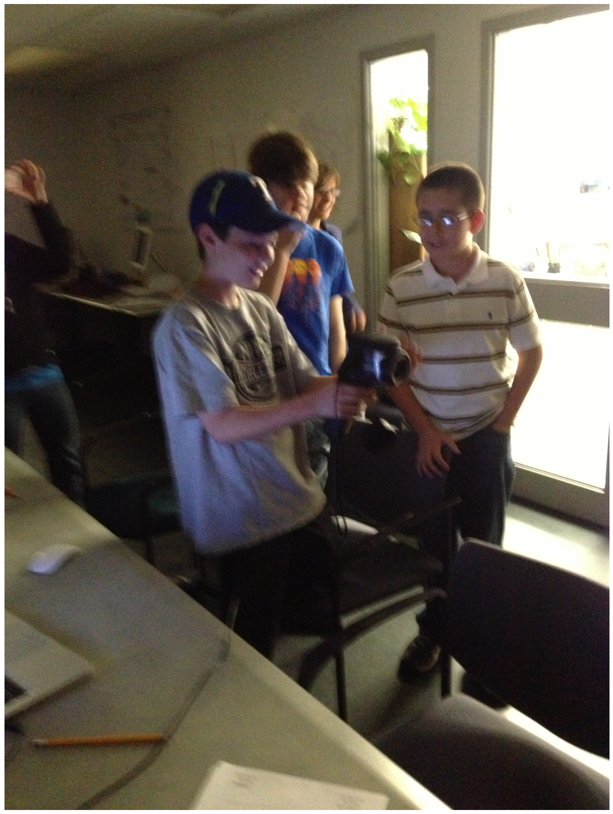


Figure 26: *Thermal image of a participant using a piece of fabric to make himself "invisible" to the IR camera*

Figure 27: *Thermal image of ice cream bar coated in cookie crumbs while still inside wrapper*

tween two solids. Seven out of 12 (4 sixth graders and 3 seventh graders) participants provided an explanation that demonstrates at least a general understanding of convection stating in general that convection is the transfer of heat or energy through a liquid or air. Ten out of 12 (5 sixth grader and 5 seventh graders) participants provided an explanation that demonstrates at least a general understanding of radiation. Participants reported that radiation is heat or energy given off or coming from an object. The students' responses to the questions after completing the activities seems to suggest some level of engagement for all participants.

Overall, participants enjoyed using the toolkit describing it as "fun", "cool", "interesting", "interactive", "engaging", "informative", "awesome" and "exciting". Participants liked the hands-on and educational aspects of the toolkit. One participant said, "We're actually handling everything which gets the point across far better for me." While another stated, "I thought the project was fun but it [also] taught you about the subject." Eleven[9] out of 12 participants said they would like to use the toolkit at school and that it helped them visualize the different modes of heat transfer because they could see the heat move through the objects. Notably, one participant said the toolkit helped him visualize the different modes of heat transfer "quite a lot because you could actually see how the heat was moving."

Further testing of the toolkit, with a larger number of students, is necessary to better understand the effects the toolkit might have on student engagement and understanding of heat transfer. The preliminary testing results presented above indicate that students found the toolkit engaging and exciting and suggest further testing of the toolkit would be worthwhile.

[9] One participant said maybe.

7 Future Developments

Because this application was designed for students in grades 6-8, the quantitative output is limited to a basic temperature change over time. In order to appeal to a more sophisticated audience of high-school and college-aged students, additional quantitative outputs can be added to the existing template. Depicting isothermal mappings of the thermal image would allow students to understand the migration of constant temperatures through the image over time. Another possible feature is to allow users to plot temperatures of multiple locations on the thermal video at the same time. In order to cater to various skill levels, the user would be able choose between the basic and advanced operating modes.

In future work it would be advantageous to develop a website hosting the LabVIEW™ program to increase the accessibility of the software and create an environment for exchange and discussion. Users could upload recordings of their experiments, experimental findings or analysis to the website. User uploads could be organized thematically in a number of ways. Over time, the website would build a substantial database of thermal videos and analysis which could act as a reference and inspiration for future investigations.

Eventually the toolkit and potential developments described above will be tested on a proper curriculum to show that the learning process is enhanced by the use of IR camera and LabVIEW™ program in the classroom.

8 Conclusion

The use of an IR camera as an educational tool in the classroom creates both advantages and disadvantages. The biggest obstacle facing the introduction of the IR camera into the classroom is its cost. Even as the price of the IR camera continues to decrease, it will never be more economically feasible than simulations that can be accessed for free online. The IR camera cannot be successfully integrated unless the ratio of cameras to students is low enough to permit the students to work in small groups.

In this thesis a set of reproducible experiments was developed to demonstrate the ease with which the IR camera allows students to examine and explore heat transfer in real time. To further take advantage of the IR camera, a software program that works with the IR camera in real time was developed. This hardware/software toolkit was then tested by six and seventh graders to investigate the its capacity to create student engagment with heat tranfer phenomena. The usability test results showed that students were engaged and excited when exploring heat transfer concepts using the toolkit. However, further testing would be required to show that the toolkit actually increases students' understanding of heat transfer.

The IR camera presents many advantages. It allows students to visualize the invisible processes of heat transfer in the environment in which they occur and in real time. Furthermore, the IR camera is user-friendly requiring very little knowledge on the part of the user of the phenomena being studied. When combined with the LabVIEW™ software program that allows students to track temperature change in the thermal video over time, students can lead their own investigations. Moreover, these investigations can be shared with a larger group, providing a basis for discussion and further inquiry.

Appendix A Participant Background Information

P#	Gender	Grade	Have you ever used an IR camera?	Have you ever used LabVIEW?	Have you been introduced to heat transfer in class?
P1	M	6	No	No	Yes
P2	M	6	No	No	No
P3	M	7	No - but seen them in video games and movies	No	Yes
P4	M	6	No - seen an IR camera in Photo Booth on iPad	No	No
P5	M	6	No	No	Yes
P6	M	6	No	No	Yes
P7	M	7	No - familiar with IR camera but never used one	No	Yes
P8	M	7	No	No	Yes
P9	M	7	No	No	Yes
P10	M	7	Yes - teacher brought one into class	No	Yes
P11	F	6	No - but has heard of one	No	No
P12	M	6	No – knows what an IR camera does but has not seen one	No	No

Table A1: *Background information of students who participated in the preliminary toolkit testing*

Appendix B Pre-activity Survey Detailed Responses

Question 1: Explain what you think heat transfer is.

Nine out of 12 (4 sixth graders and 5 seventh graders) participants provided an explanation that demonstrated at least a general understanding of heat transfer. Participant comments are provided below.

Generally correct explanations:

- Heat transfer is "when heat moves/is transferred from one object/thing to another." (P1, P4, P10, P11)
- Heat transfer is "when more heat is transferred to less heat to equalize." (P3)
- Heat transfer is the "transfer of energy through something gas/liquid/solid." (P6)
- "Heat transfer is the movement of heat energy from one object to another." (P7)
- Heat transfer is "energy transferred from molecules in one object to another." (P8)
- "Heat transfer is the transfer of thermal energy from one object to another." (P9)

Incorrect explanations:

- Heat transfer is "the transfer of heat." (P2)
- Heat transfer is "something that takes heat and shows how hot it is." (P5)

- Heat transfer is “when you try to transfer heat.” (P12)

Question 2: Explain what you think conduction is.

Two out of 12 (3 sixth and 5 seventh graders) participants provided an explanation that demonstrated at least a general understanding of conduction. Participant comments are provided below. Note that incorrect comments are only listed if the participants provided an explanation.

Generally correct explanations:

- Conduction is “the transfer of heat energy between two touching objects.” (P7)
- Conduction is “heat transfer through physical contact.” (P9)

Incorrect explanations:

- Conduction is “transfer of energy through friction.” (P1)
- “Conduction is what helps concentrate heat.” (P3)
- Conduction is “one object attracting heat or energy.” (P4)
- “Conduction is when heat is being produced in one area and moving around.” (P5)
- Conduction is the “transfer of energy.” (P6)
- “To conduct is to be able to transfer electricity or energy.” (P10)
- Conduction is “being able to have a source of energy pass through something and come out the same as before.” (P11)
- Conduction is “an object that can keep in heat.” (P12)

Question 3: Explain what you think convection is.

Four out of 12 (2 sixth graders and 2 seventh graders) participants provided an explanation that demonstrated at least a general understanding of convection. Participant comments are provided below. Note that incorrect comments are only listed if the participants provided an explanation.

Generally correct explanations:

- "Convection is when heat from below something warms it up and when warmed its density decreases and risers where it cools down to be warmed again." (P4)
- "Convection is when heat goes up and turns cool and then the cool air comes down and turns into hot air." (P5)
- "I cant explain, but I can give an example. When you put a pot of water on a burner of a stove, the water at the bottom heats up and rises, creating currents." (P7)
- Convection is "heat transfer through fluid movements." (P9)

Incorrect explanations:

- Convection is "like an oven." (P2)
- "Convection is what drives away heat/traveling to a colder area." (P3)
- Convection is "the process of heat melting an object." (P12)

Question 4: Explain what you think radiation is.

Four out of 12 (1 sixth grader and 3 seventh graders) participants provided an explanation that demonstrated at least a general understanding of radiation. Participant comments are provided below. Note that incorrect comments are only listed if the participants provided an explanation.

Generally correct explanations:

- Radiation is “energy coming from an object.” (P6)
- Radiation is “the transfer of heat through empty space.” (P7)
- “Radiation is heat let off from an object.” (P8)
- Radiation is “heat transfer that uses neither physical contact nor fluid.” (P9)

Incorrect explanations:

- Radiation is nuclear heat.” (P1)
- Radiation is what comes out of solar and geothermal.” (P3)
- Radiation is something that nuclear reactors create which is very bad.” (P4)
- Radiation is light that is given off by infrared light and gives off heat.” (P5)
- Radiation are waves of energy such as x-rays waves and UV light.” (P10)
- Radiation is waves of some sort coming off of something and disrupting the air or gas.” (P11)
- Its when something is toxically dangerous.” (P12)

Appendix C Post-activity Interview Heat Transfer Question Responses

Question 1: Explain what you think heat transfer is.

Ten out of 12 (5 sixth graders and 5 seventh graders) participants provided an explanation that demonstrated at least a general understanding of heat transfer. Participant comments are provided below.

Generally correct explanations:

- Heat transfer is “when heat moves/is transferred from one object/thing to another.” (P1, P4, P6, P10, P11)
- Heat transfer is “when heat goes from hotter places to colder places.” (P3)
- Heat transfer is “when heat is transferred through things.” (P5)
- Heat transfer is the “transfer of energy through something gas/liquid/solid.” (P6)
- “Heat transfer is the movement of heat energy from one object to another.” (P7)
- Heat transfer is “the transfer of energy between items (in the form of heat).” (P8)
- “Heat transfer is the transfer of thermal energy from one object to another.” (P9)
- Heat transfer is “when energy is transferred into anything.” (P12)

Incorrect explanations:

- Heat transfer is “the transfer of heat.” (P2)
- Heat transfer is “heat from something else is put on to something.” (P11)

Question 2: Explain what you think conduction is.

Eight out of 12 (2 seventh graders) participants provided an explanation that demostrates at least a general understanding of conduction. Participant comments are provided below. Note that incorrect comments are only listed if the participants provided an explanation.

Generally correct explanations:

- Conduction is “when heat is transferred through a solid.” (P3)
- Conduction is “energy going through an object.” (P6)
- Conduction is “heat energy movement between two solids.” (P7)
- Conduction is “the transfer of heat between touching objects.” (P8)
- Conduction is “heat transfer through physical contact, specifically solids.” (P9)
- Conduction is “the transfer of heat to a solid.” (P10)
- Conduction is “heat coming and going through a solid.” (P11)
- Conduction is “when energy passes through a solid.” (P12)

Incorrect explanations:

- Conduction is “evaporation.” (P1)
- Conduction is “one object conducting something.” (P4)
- “Conduction is when heat transferred through something.” (P5)

Question 3: Explain what you think convection is.

Seven out of 12 (4 sixth graders and 3 seventh graders) participants provided an explanation that demonstrates at least a general understanding of convection. Participant comments are provided below. Note that incorrect comments are only listed if the participants provided an explanation.

Generally correct explanations:

- Convection is "heat transfer through air." (P1)
- Convection is "when liquids change temperatures." (P3)
- Convection is "heat rising and falling." (P4)
- Convection is "heat transfer through fluid movements." (P9)
- Convection is "the transfer of heat to a liquid." (P10)
- Convection is "heat coming and going through liquids." (P11)
- Convection is "when energy passes through liquid." (P12)

Incorrect explanations:

- Convection is "like a convection oven." (P2)
- Convection is "when heat turns cool." (P5)
- Convection is "the process of heating and cooling." (P6)
- Convection is "the transfer of heat between open spaces." (P8)

Question 4: Explain what you think radiation is.

Ten out of 12 (5 sixth grader and 5 seventh graders) participants provided an explanation that demonstrates at least a general understanding of radiation.

Participant comments are provided below. Note that incorrect comments are only listed if the participants provided an explanation.

Generally correct explanations:

- Radiation is “heat emitted from a source.” (P3)
- Radiation is “heat given off something.” (P4)
- “Radiation is when something is giving off heat.” (P5)
- Radiation is “energy given off by an object.” (P6)
- Radiation is “heat energy moving through empty space.” (P7)
- “Radiation is heat let off from an object.” (P8)
- Radiation is “heat transfer that uses neither physical contact nor fluid.” (P9)
- Radiation is “the transfer of heat through ’air’.” (P10)
- Radiation is “heat emitted from something in to air, ect.” (P11)
- Radiation is “the heat that anything gives off. (P12)

Incorrect explanations:

- Radiation is “heat transfer[10].” (P1)

[10] While this answer is technically correct, the participant did not demonstrate in any way that he understood what radiation is or how it works.

Appendix D Three User-defined Energy2D Simulations

To better understand Energy2D, three user-defined simulations were performed testing the basic heat transfer mechanisms of conduction, convection, and radiation. A detailed explanation of these simulations is provided below.

D.0.1 Conduction

Using the draw features in Energy2D, the experimental setup for conduction was reconstructed, Figure D28. Table D2 shows the thermophysical properties of the materials used in the model to simulate the experiment. These values must be determined and entered into the model for each material or object before running the simulation.

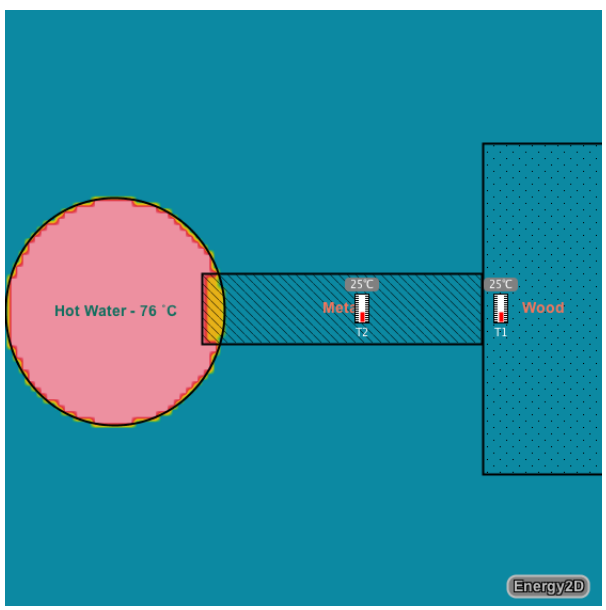


Figure D28: *Energy2D model setup of conduction experiment*

After constructing the conduction setup and inputting the thermophysical property values, the model was run producing the simulation shown in Fig-

Thermophysical Properties of Conduction Model Materials				
	Water	Aluminum 6061 Temper T6	Wood (Yellow Pine)	Air
Length (x) [m]	0.075	0.1	0.036	0.427
Width (y) [m]	0.081	0.025	0.086	0.262
Initial Temperature [˚C]	76	25	25	25
z diffusivity [1/s]	N/A	N/A	N/A	0.0187
Thermal Conductivity [W/m˚C]	668	167	0.15	0.0263
Specific Heat [J/kg˚C]	4.1936	1074	2805	1007
Density [kg/m^3]	974.08	2760	640	1.1614
Kinematic Viscosity [m^2/s]	N/A	N/A	N/A	Default Value
Thermal Buoyancy [m/s^2·˚C]	N/A	N/A	N/A	Default Value
Buoyancy Approximation	N/A	N/A	N/A	Default
Absorption	0.98	0.98	1	Not used

Table D2: *Thermophysical properties of materials and fluids employed in conduction experiment*

ure D29 . In this initial run the z heat diffusivity was left at its default values of zero. The center of the bar essentially reaches the temperature of the water, which is not realistic due to the substantial energy losses via convection to the surrounding fluid.

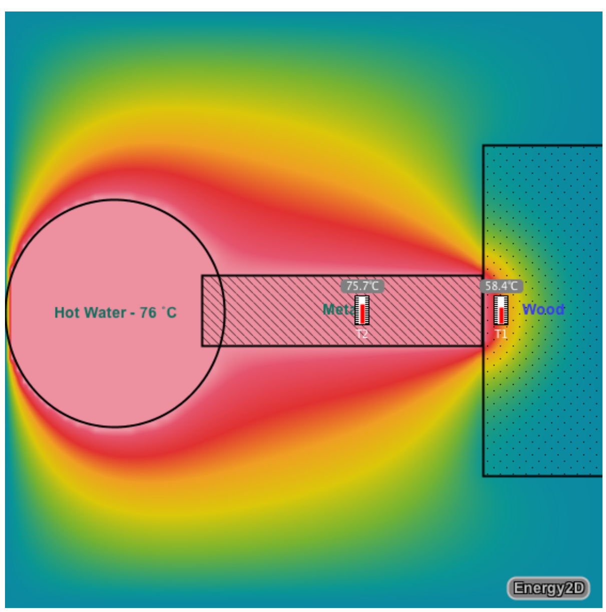


Figure D29: *Screenshot of conduction simulation with thermal conductivity* $0.0263\ W/(m \cdot ^\circ C)$

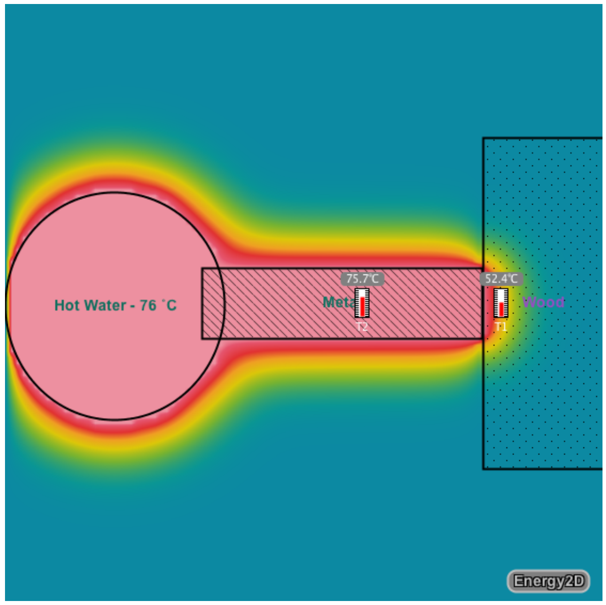


Figure D30: *Screenshot of conduction simulation with thermal conductivity* $1 \cdot 10^{-4}$ $W/(m *^{\circ}\ C)$

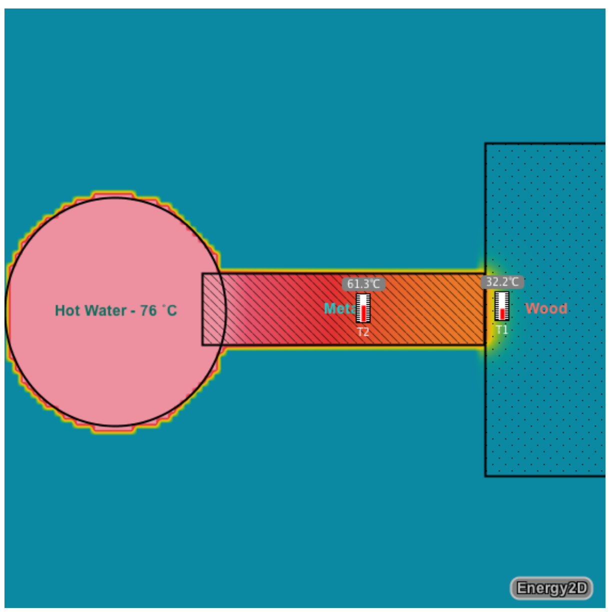


Figure D31: *Screenshot of conduction simulation with thermal conductivity* 0 $W/(m \cdot^{\circ} C)$

To more accurately model the experiment presented in section 6.1, the thermal conductivity of air and the z diffusivity (i.e., energy lost to the surroundings) values were adjusted. First, the effects of the thermal conductivity parameter were examined. As this value was decreased the amount of thermal energy conducted to the surrounding fluid decreased, but the center temperature of the bar did not change, as depicted in Figure D30. Next, multiple iterations of the simulation were run to determine the value of heat diffusion necessary to create the appropriate amount of thermal energy loss. A model that produced simulated results closely matching thermal conduction captured with the IR camera was achieved by setting the thermal conductivity to zero and z diffusivity 0.0187 $1/s$ and is shown in Figure D31.

D.0.2 Convection

The standard natural convection simulation model in Energy2D was modified using the draw tools to correspond with the aforementioned natural convection experiment in section 6.2. Figure D32 shows the model setup in Energy2D. Before proceeding with the simulation analysis, the thermophysical properties of the materials used in the experiment were determined, and are shown in Table D3, and the model parameters were adjusted. The boundary conditions of the model were set to constant temperature with each edge of the model set to 25 $°C$. Parameters not listed in Table D3 were left at their default values.

A snapshot of the resulting simulation is shown in Figure D33 below. Clearly, the initial simulation did not produce results similar to those observed in the experiment. One distinct difference is the temperature reading of 14.76 $°C$ inside the channel. How could this temperature be lower than the initial temperature of 25 $°C$ of the surrounding fluid? At what point did the cold air become part of the simulation? Figure D34 shows that just after the model starts, cold air enters from the upper boundary. There are two model properties that contribute greatly to simulation inaccuracies, thermal buoyancy and buoyancy approximation, making them a good starting point

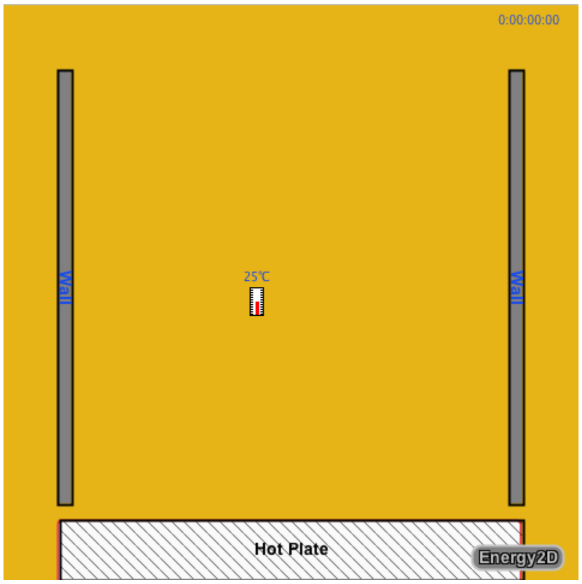


Figure D32: *Energy2D model setup of convection experiment with no lid*

Thermophysical Properties of Convection Model Materials			
	Walls (2)	Hot Plate	Air
Length (x) [m]	0.2	8	10
Width (y) [m]	7.05	1	10
Initial Temperature [°C]	25	100	25
z diffusivity [1/s]	N/A	N/A	0
Thermal Conductivity [W/m·°C]	0.18	3.98	1
Specific Heat [J/kg·°C]	1340	8.08	1007
Density [kg/m^3]	930	2600	1.1614
Kinematic Viscosity [m^2/s]	N/A	N/A	$1.559*10^{-4}$
Thermal Buoyancy [m/s^2·°C]	N/A	N/A	$2.5*10^{-6}$
Buoyancy Approximation	N/A	N/A	All-cell average
Absorption	0.98	0.9	Not used

Table D3: *Thermophysical properties of materials and fluids employed in convection experiment*

to begin adjusting the model to investigate this problem.

Although changing the buoyancy approximation decreased the amount of cold air introduced into the model, the overall results were similar to those in

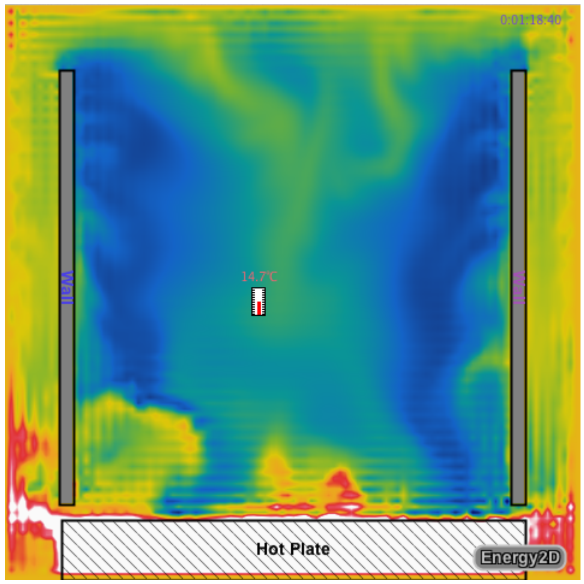


Figure D33: *Screenshot of natural convection simulation with thermal buoyancy of air at default value,* $2.5 \cdot 10^{-4}\ m/(s^2 \cdot^\circ C)$

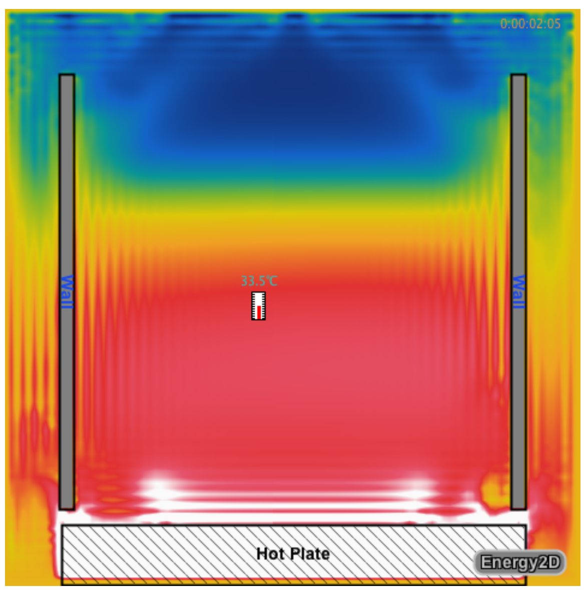


Figure D34: *Screenshot of natural convection simulation showing the introduction of cold air*

Figure D33. However, adjusting the thermal buoyancy altered the simulated results significantly. Increasing this parameter by a factor of ten caused the simulation to crash, but decreasing it reduced the amount of cold air that was introduced into the system and created a less turbulent flow allowing for a reasonable representation of the experiment. Figure D35 above shows results that are a good representation of the experimental results. These results were achieved by setting the thermal buoyancy to $2.5 \cdot 10^{-6}\ m/(s^2 \cdot^\circ C)$. Similarly, results showing the effects of a ceiling in Figure D36 were obtained with a thermal buoyancy of $2.5 \cdot 10^{-5}\ m/(s^2 \cdot^\circ C)$.

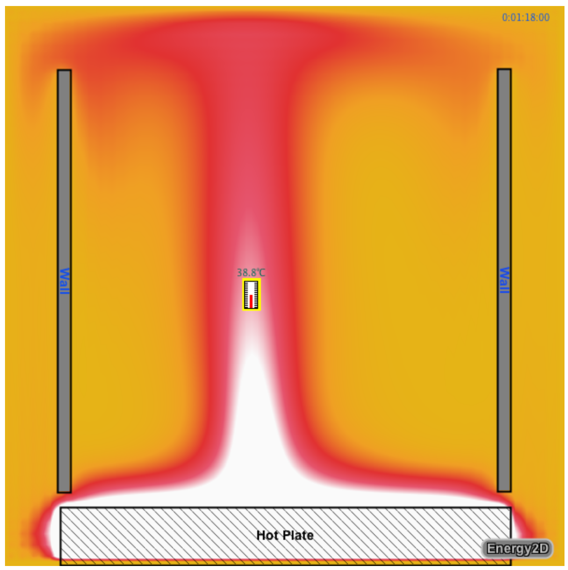


Figure D35: *Screenshot of natural convection simulation with thermal buoyancy of air at default value,* $2.5 \cdot 10^{-6}\ m/(s^2 \cdot^\circ C)$

Other model properties that play more peripheral roles were studied. The z heat diffusivity value was increased gradually from zero. This action resulted in simulations that remained the same as those in Figure D35 but took much longer to develop (see Figure D37). However, a critical point was discovered after increasing the parameter to a value of 0.005 at which point the energy transfer was halted. Neither of these cases produced results better than those obtained in Figure D35, and the default value of zero was accepted for the model.

Next radiation was introduced into the model. Figure D38 shows the sim-

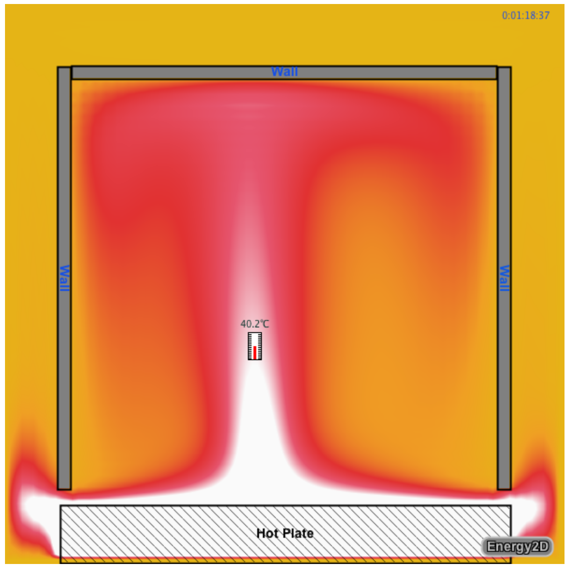


Figure D36: *Screenshot of natural convection simulation with thermal buoyancy of air at default value,* $2.5 \cdot 10^{-6}$ $m/(s^2 \cdot ^\circ C)$

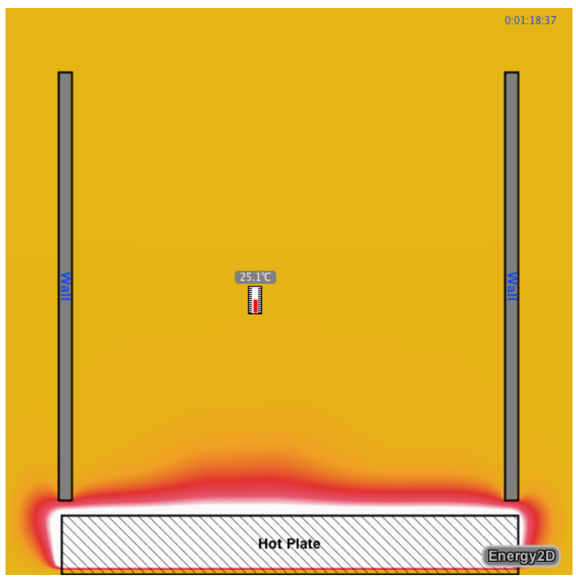


Figure D37: *Screenshot of natural convection simulation with thermal buoyancy of air at default value,* $2.5 \cdot 10^{-6}$ $m/(s^2 \cdot ^\circ C)$ *and z heat diffusivity setting of 0.005*

ulated results with radiation present. To account for radiation the "sunny" box must be activated (this is accomplished by checking the box). The figure shows that the convective results remain unchanged from the simulated results

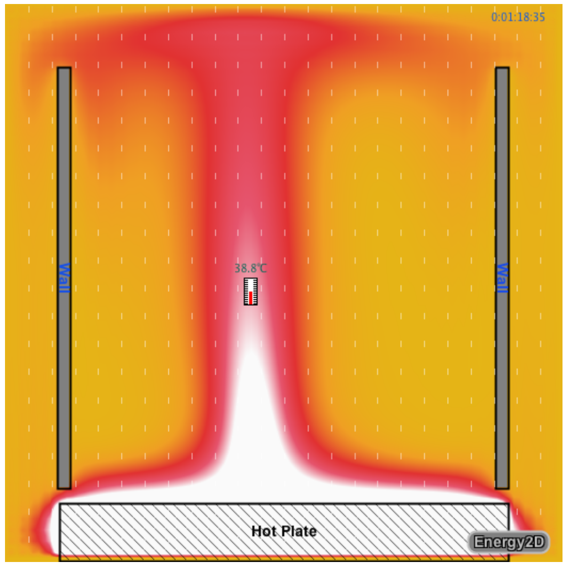


Figure D38: *Screenshot of natural convection simulation with thermal buoyancy of air at default value,* $2.5 \cdot 10^{-5}$ $m/(s^2 \cdot ^\circ C)$ *and z heat diffusivity setting of 0.005*

in Figure D35, meaning the model is currently unable to qualitatively simulate radiative heat transfer.

D.0.3 Radiation

To simulate the hands-on experiment a model was constructed in Energy2D. The important features of the experiment incorporated into the model were the screen and jar. The model setup is shown in Figure D39. The thermophysical properties of the objects involved in the experiment were determined and entered into the model. These values and are listed in Table D4. The boundary conditions were set to constant temperature with each respective edge of the model set to 25 $^\circ C$. For the initial run the thermal buoyancy were left at their default values.

Figure D40 shows that the simulation results are reasonable in the sense that they are quantitatively but not qualitatively similar to the experimental results. The virtual thermometer located at the center of the rectangle reaches approximately the same temperature detected by the crosshair of the IR camera in the experiment; however, there is discrepancy between the pattern that appears on the rectangle and the pattern that appears on the screen. The experimental results indicate that we would expect to see the temperature of the rectangle decrease when moving away from the center towards the ends while the simulated results show the temperature increases towards the end of the rectangle.

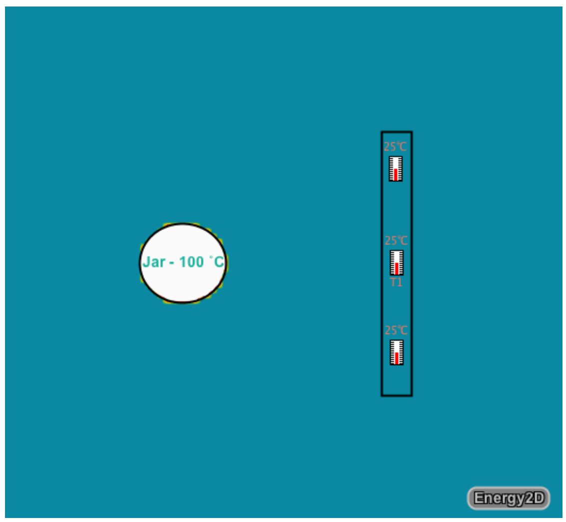


Figure D39: *Energy2D model setup of radiation experiment without aluminum foil; all thermometers read* 25 °C

The model was also modified to simulate the experiment of the jar containing cold water. However, the simulation breaks down when the temperature of the circle, which represents the jar, is set to anything less than 19.68 °C. At temperatures close to this the "rays" of radiation emitted by the circle become sporadic, and at temperatures that are much lower the "rays" vanish. Even when the temperature of the circle is set to 20 °C, the temperature of the rectangle increased. The experimental results in section D.0.1 showed that the temperature of the rectangle should actually decrease since the screen is transferring more thermal energy via radiation to the jar than the jar is to the

Thermophysical Properties of Radiation Model Materials				
	Jar - Hot	Jar - Cold	Screen	Air
Length (x) [m]	0.2	0.2	8	10
Width (y) [m]	7.05	7.05	1	10
Initial Temperature [˚C]	91	0.1/11.4	25	25
z diffusivity [1/s]	N/A	N/A	N/A	0
Thermal Conductivity [W/m·˚C]	0.18	0.18	3.98	1
Specific Heat [J/kg·˚C]	1340	1340	8.08	1007
Density [kg/m^3]	930	930	2600	1.1614
Kinematic Viscosity [m^2/s]	N/A	N/A	N/A	$1.559 * 10^{-4}$
Thermal Buoyancy [m/s^2·˚C]	N/A	N/A	N/A	$2.5 * 10^{-6}$
Buoyancy Approximation	N/A	N/A	N/A	All-cell average
Absorption	0.98	0.98	0.9	Not used

Table D4: *Thermophysical properties of materials and fluids employed in radiation experiment*

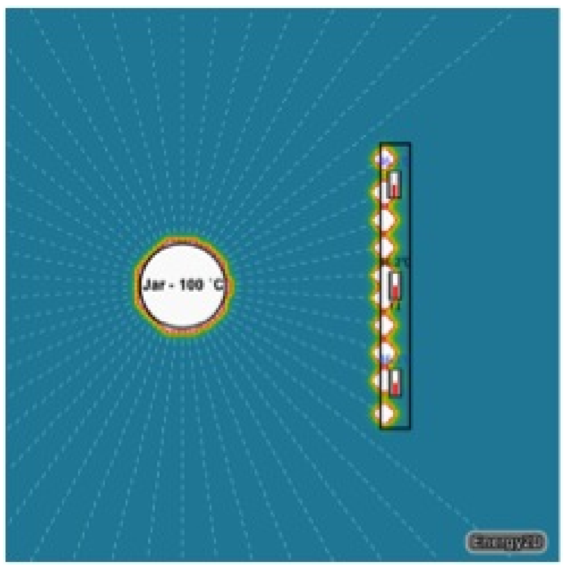


Figure D40: *Screenshot of radiation simulation with thermal buoyancy of air adjusted,* $2.5 \cdot 10^{-6}\ m/(s^2 \cdot {}^\circ C)$*; temperature readings of thermometers in rectangle from top to bottom are* $46.3\,^\circ C$, $36.2\,^\circ C$ *and* $46.3\,^\circ C$*, respectively*

screen, which is not seen in the simulation.

The next step was to reproduce the experimental results that occur when the jar is wrapped in aluminum foil, namely to prevent the thermal radiation emitted by the jar from reaching the screen. Four small rectangles were used

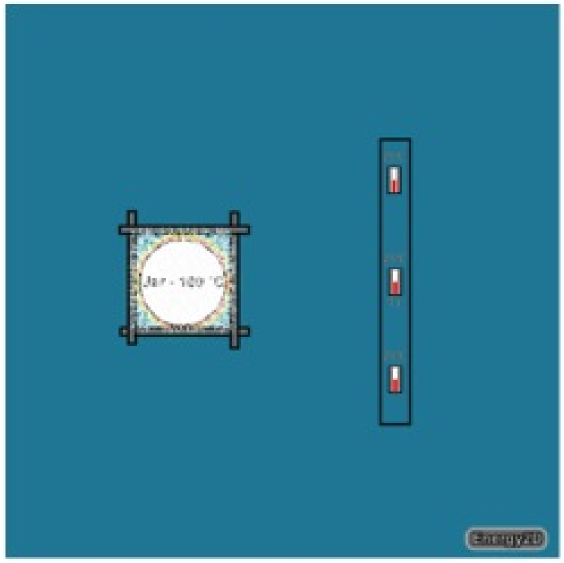


Figure D41: *Screenshot of radiation model simulating effects of aluminum foil on thermal radiation; all thermometers in rectangle read* $25°C$

to represent aluminum foil covering the jar, see Figure D41. Each rectangle was modified to become a reflector. Simulated results show that the barriers enclosing the circle reflect the thermal radiation waves and, as a result, there is no temperature change anywhere in the rectangle.

After achieving a working model several of the other parameters were altered to examine their effects on the simulated results. The first adjustment was to activate the ”sunny” parameter, which introduces radiation from a source, such as the sun, outside of the model boundaries. Figure D42 shows thermal radiation entering through the upper boundary at a 90 ° angle and having no effect on the temperature of the rectangle. Modifying the various radiation properties only changes the simulation in appearance and not numerically.

Next, convection was introduced by checking the box labeled Convection in the fluid properties and the model was run producing results shown in Figure D43. Again, the results show that activating this property does not

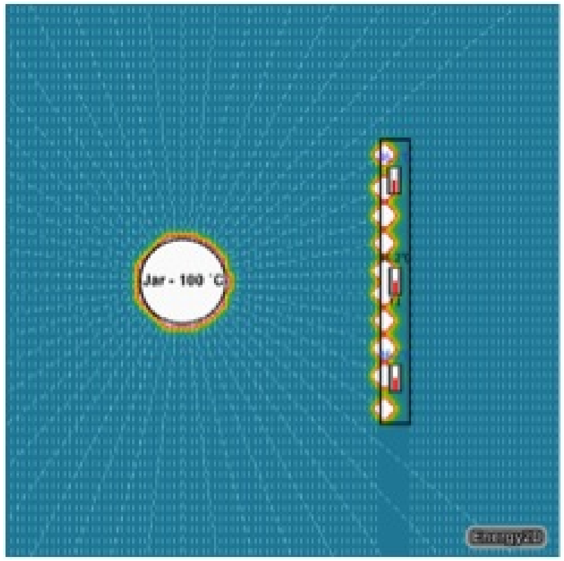


Figure D42: *Screenshot of radiation simulation with radiation from outside boundaries present and thermal buoyancy of* $2.5 \cdot 10^{-6} m/(s^2 \cdot^\circ C)$

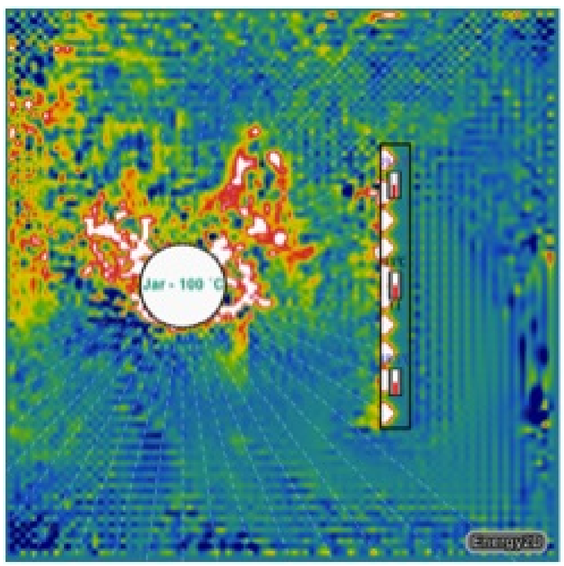


Figure D43: *Screenshot of radiation simulation with thermal buoyancy of air adjusted,* $2.5 \cdot 10^{-6}\ m/(s^2 \cdot^\circ C)$

affect the model quantitatively. However, the fluid properties can be adjusted. The thermal buoyancy was decreased to a value of $2.5 \cdot 10^{-5}\ m/(s^2 \cdot^\circ C)$ to generate a more realistic visual representation of thermal energy loss from the

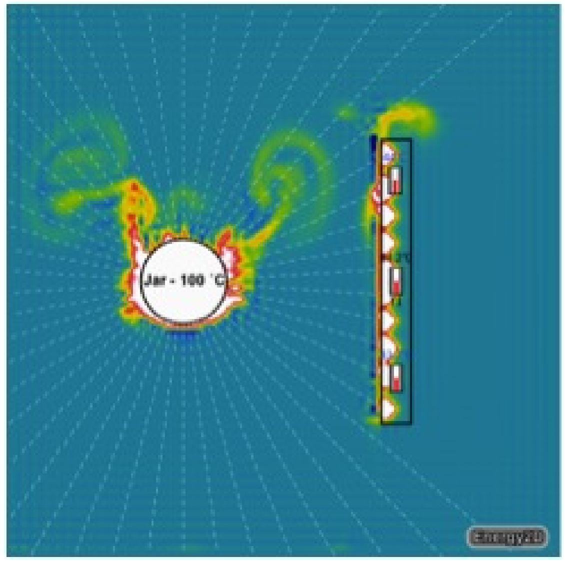


Figure D44: *Screenshot of radiation simulation with ceiling and thermal buoyancy of* $2.5 \cdot 10^{-5}\ m/(s^2 \cdot ^\circ C)$

objects via convection, shown in Figure D44.

D.1 Analysis and Conclusions

Energy2D is an excellent simulation software for many classroom activities. Students with limited understanding of heat transfer can view pre-loaded simulations, adjusting parameters to see their influence on the simulation. User-defined simulations are available to users who already have a basic understanding of the heat transfer phenomena and can access the specific geometric, thermal, and optical properties of the environment they wish to simulate. Affordability, accessibility and its ability to generate realistic visualizations of heat transfer phenomena make Energy2D a viable tool for teaching heat transfer in the classroom.

Appendix E How to Set the Parameters of an IR Camera

There are five parameters that are dependent on the environment in which the IR camera is being used and must be set properly to acheive accurate results. These parameters are emissivity, atmospheric temperature, relative humidity, distance and reflected, sometimes referred to as apparent, temperature.

The atmospheric temperature is the temperature of the atmosphere in which you are using the IR camera. This can be determined using a thermometer. Similarly, the relative humidity of the environment in which the IR camera is being used can be determined by using a hygrometer. However, unless the relative humidity is extremely high or low, it does not have a significant affect on the output and can be approximated. The distance is simply the distance between the IR camera and the object being observed, in meters.

The IR camera can be used to determine the emissivity and reflected temperature of the targeted object. To determine the emissivity of an object using an IR camera, the object's reflected tempeature must first be determined. The reflected temperature accounts for the background radiation that interferes with the object being observed (i.e., it accounts for the energy reflected from the measured surface). For example, when a shiny material such as aluminum is viewed through the lens of an IR camera, it will reflect radiation emitted by nearby objects. As such, a false temperature reading will occur if the background radiation is not accounted for. To calculate the reflected temperature of an object, set the known parameters (i.e., atmospheric temperature, distance and relative humidity). Crumple up a piece of aluminum foil. Uncrumple the foil and place it in front of the object to be measured, making sure that the foil is in the same place as the target. Using the average temperature function on the IR camera, aim the camera at the target and note the average temperature indicated by the camera. This is the reflected temperature of the target.

Now that all other parameters have been determined, the emissivity of the object can be found. Emissivity is the relative ability of a material's surface to emit energy in the form of radiation. Emissivity is the most important parameter to set correctly because it has the greatest effect on the temperature distribution produced by the IR camera. To use the IR camera to determine the emissivity, place a piece of tape with known emissivity on the object's surface. After setting the remaining parameters to the correct value, set the emissivity of the IR camera to the value of the tape (i.e., 0.95 for electrical tape). Heat the object so that it is at least 20 $^{\circ}C$). Determine the temperature of the piece of tape using the IR camera. This is the surface temperature of the object. Move the crosshairs of the IR camera to the original surface and adjust the emissivity value in the IR camera until the object's actual surface temperature is reached. This step is not necessary if the emissivity of the object is known or can be looked up using a reference source such as a heat transfer textbook. If the material's emissivity is not easily determined, then a thermomerter used to measure the object's surface temperature can be used to determine the its emissivity.

References

[1] Ruddock, Wayne, 2011, "The NFPA and Its Effect on Infrared Thermography and Your Infrared Electrical Inspection Program," *Uptime Magazine*, T. O'Hanlon and K. R. O'Hanlon, eds., Ft. Myers, Floride, Aug/Sep, pp. 28-29.

[2] Cahyadi, V., 2004, "The Effect of Interactive Engagement Teaching on Student Understanding of Introductory Physics at the Faculty of Engineering, University of Surabaya, Indonesia," Higher Education Research and Development, **23**(4), pp. 455-464.

[3] Ferguson, D., 2001, "Technology in a Constructivist Classroom," Information Technology in Childhood Education Annual," **2001**(1), pp. 45-55.

[4] Hake, R., 1997, "Interactive-engagement Versus Traditional Methods: A Six-thousand-student Survey of Mechanics Test Data for Introductory Physics Courses," American Journal of Physics, **66**(1), pp. 64-74.

[5] Becker, H. J., and Ravitz, J., 1999, "The Influence of Computer and Internet Use on Teachers' Pedagogical Practices and Perceptions," Journal of Research on Computing and Education, **31**(4), pp.356-384.

[6] Schofield, J. W., 1997, "Computers and Classroom Social Processes: A Review of the Literature," Social Science Computer Review, **15**(1), pp. 27-39.

[7] Smith, M. and Broom, M., 2003, "The Landscape and Future of the Use of Technology in K-12 Education," *Technology Applications in Education: A Learning View,* O'Neil, H. F. Jr., and R. S. Perez, eds., Mahwah, NJ, Lawrence Erlbaum Associates, pp. 3-30.

[8] Anderson, R., Anderson, R., Davis, K. M., Linnell, N., Prince, C., and Razmov, V., 2007, "Supporting Active Learning and Example Based Instruction with Classroom Technology." SIGCSE Bull. **39**(1), pp. 69-73.

[9] Means, B., and Olson, K., 1995, "Technology and Education Reform: Technical Research Report," U.S. Department of Education, http://www.ed.gov/pubs/SER/Technology/ [2013, April 5].

[10] Kulik, J. 1994. "Meta-analytic Studies of Findings on Computer-based Instruction," *Technology assessment in education and training,* Baker, E. L., and O'Neil, H. F., Jr., eds., Hillsdale, NJ, Lawrence Erlbaum Associates, pp. 9-33.

[11] Barak, M., and Hussein-Farraj, R., 2012, "Integrating Model-based Learning and Animations for Enhancing Students' Understanding of Proteins Structure and Function," Research in Science Education, **43**(2), pp. 619-636.

[12] Barak, M., and Dori, Y. J., 2011, "Science Education in Primary Schools: Is an Animation Worth a Thousand Words?" Journal of Science Education and Technology, **20**(5), pp. 608-620.

[13] Williamson, V. M., and Abraham, M. R., 1995, "The Effects of Computer Animation on the Particulate Mental Models of College Chemistry Students," Journal of Research in Science Teaching, **41**(5), pp.481-512.

[14] Barak, M. and Dori, Y. J., 2005," Enhancing Undergraduate Students'Cchemistry Understanding Through Project-based Learning in an IT Environment," Science Education, **89**(1), pp. 117-139.

[15] Barak, M., Ashkar, T., and Dori, Y. J., 2011, "Learning Science Via Animated Movies: Its Effect on Students' Thinking and Motivation," Computer and Education, **56**(3), pp. 839-846.

[16] Yarden, H., and Yarden, A., 2010, "Learning Using Dynamic and Static Visualizations: Students; Comprehension, Prior Knowledge and Conceptual Status of a Biotechnological Method," Research in Science Education, **40**(3), pp. 375-402.

[17] Xie, C., and Hazzard, E., 2011, "Infrared Thermograhpy for Discovery Learning," Physics Teacher, **49**(6), pp. 368-372.

[18] Cabello, R., Navarro-Esbrí, J., Llopis, R., and Torrella, E., 2006, "Infrared Thermography as a Useful Tool to Improve Learning in Heat Transfer Related Subjects," International Journal of Engineering Education, **22**(2), pp. 373-380.

[19] Xie, C. Energy2D Simulation Software, available at http://energy.concord.org/energy2d/