Heat Transfer and M&Ms: Hands-on Minds-on Learning

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Drawing on hands-on minds-on learning theory, this activity is designed to help students better understand and retain somewhat abstract concepts. Heat Transfer through the mechanisms of conduction, convection, and radiation are fundamental concepts but their micro-structural aspects are obscure to students as evidenced by class discussions after assigned readings on the subject. In this activity, fourth-year mechanical engineering students are asked to create physical representations using multi-colored M&Ms (colorful round chocolate candies) of atomic and molecular-scale phenomena pertaining to conduction, convection, and radiation in solid, liquid, and gas phases of matter. Students are assigned the reading a few days in advance and asked to come to the laboratory session having thought about their physical representations. During the 100-minutes-long laboratory session, students work in teams. Each team is assigned either a solid, liquid, or gas phase. They are provided with M&Ms and cookie sheets (baking trays). They discuss, plan, and enact their representations in the first half of the session. Then, the whole class walks to each station. The students at the station give a brief informal presentation on their representation and answer questions. During this informal question & answer session, faculty organizes key features of the three modes of heat transfer on the board. Students actively contribute to the information jot on the board. Post-activity, they are provided one week to reflect on the process. In this paper, I shall present their reflections along with the activity prompts and student representations. Students have indicated superior learning outcomes due to (i) having to think about and enact physical representations; (ii) debrief information jot on the board after the activity during the question-and-answer session. In the subsequent lectures during the semester, this activity is often referred to while discussing various specific topics of Heat Transfer. Having performed this activity in the first week of classes, students present deeper modes of understanding and interest in the subject during the semester as evidenced by enhanced class participation and performance in the exams.

Introduction:

The study of heat is a difficult subject. One of the known challenges in learning Thermodynamics and Heat Transfer is the abstract nature of concepts [1]. Quantities such as amount of heat, rate of heat transfer, temperature can be measured but not seen. No wonder, people explained heat transfer as the movement of a physical substance called “caloric” until the 19^{th} century [2]. Understanding heat transfer requires cultivation of abstract thinking abilities: e.g., conduction occurs as a result of lattice vibrations and movement of free electrons; convection occurs due to molecular collisions and diffusion alongside the movement of the medium as a continuum; radiation results from intra-atomic energy transitions.

Engineering students have an earlier exposure to classical mechanics, which is concrete and deterministic. They often struggle with abstract and stochastic concepts in Thermodynamics and Heat Transfer [1]. Additionally, modern life riddled with many distractions is not conducive to

abstract thinking [3]. Finally, when students are passive receivers of knowledge in a lecture setting, they often disengage with the material and do not retain information [4], [5].

Hands-on Minds-on Learning theory derives from the earlier work of Jean Piaget [6] and involves moving back and forth between concrete objects and abstract ideas [7]. Building of tools through our earliest history has indeed contributed to the development of mind circuitry [8]. Engaging mind and hands together to produce a tactile output (such as knitting a sweater) has been shown to support brain health in managing neurological disorders such as depression, Parkinsons, and dementia [9]. Furthermore, the connection between art and abstract thinking has also been studied [10]. Thus, the inspiration for this activity draws from three sources: (i) The role of neuro-muscular engagement in sharpening the mind. (ii) The role of Art in supporting and expressing abstract thinking. (iii) The role of liberative pedagogies in facilitating whole-person engagement with the learning process.

Context and motivation:

Heat Transfer is a required course in the Mechanical Engineering curriculum. In our institution, it is taught as a culminating course in a sequence of Thermo-Fluids courses spanning 2nd year (Thermo-Fluids I), 3rd year (Thermo-Fluids II), and 4th year (Heat Transfer). Thus, students bring the knowledge of the fundamentals of Thermodynamics and Fluid Mechanics to this course. I teach this entire course sequence and apply liberative pedagogies [11]. An essential feature of my teaching philosophy is to steer them away from superficial learning (memorization / recall) and towards deeper learning (analysis / application / synthesis) [12].

In my earlier years of teaching, I found that students would either not do the reading or would repeat sentences from the book if reading was assigned for points. This was usually motivated by their need to earn points. Later class discussions would reveal very rudimentary knowledge of the underlying phenomena. At the same time, I noticed that my students exhibited much deeper engagement with the material and greater initiative when assigned hands-on work *e.g.* projects to build something or demonstrate an idea [13]. Understanding the role of hands-on minds-on learning, I devised this simple activity with minimal materials to help students acquire a deeper understanding of the fundamental concepts of heat transfer. Its current form has evolved over the years through a process of feedback and reflection.

The purpose of this activity is to have students think about and engage with the material deeper than they would if it were part of a lecture / passive reception of knowledge. The purpose is *not* to develop a quantitatively accurate model of the three modes of heat transfer. Thinking through the modes of convection and radiation, this work generates questions in students' minds as to how to make these physical representations given that these two modes do not lend themselves to simplistic molecular representations using M&Ms.

Methods:

This work is performed in the first week of classes. It comprises of a reading assignment followed by in-person hands-on work and informal presentations, which are accompanied by an information jot on the board along with explanations provided by me. The information jot draws from student presentations, their questions, and my Socratic questions to them. The students are given one week after the activity to reflect on their experience. They submit a reflective narrative on their experience. The work presented in this paper is aggregated over the course of several years.

Pre-activity:

Students are provided the following prompts on the first day of the classes on a Monday:

- Read Sections 1-6, 1-7, 1-8 of the textbook [14] to develop basic understanding of conduction, convection, and radiation processes at the molecular level before this week's laboratory session on Thursday.
- Plan to demonstrate the three modes of heat transfer using M&Ms during laboratory session on Thursday (of the same week).
- Reflect on your learning via reading vs. applying reading concepts using M&Ms. Reflections are due by next Thursday.

The class size is no more than 20 students, usually around 15 students. This is a team assignment, and the teams are formed on Monday. Students are encouraged to collaborate with their team-mates prior to the laboratory session to brainstorm ideas for physical representation.

The laboratory session:

There are three student teams. Each team is assigned a phase of matter – solid, liquid, or gas. Each team is asked to represent heat transfer via conduction, convection, and radiation in their assigned phase of matter. So, a team that is assigned solid phase, will simulate conduction, convection, and radiation modes of heat transfer in solids. Likewise, a team that is assigned liquid phase, will simulate conduction, convection, and radiation modes of heat transfer in liquids. And the team that is assigned gas phase, will simulate conduction, convection, and radiation modes of heat transfer in gases.

Initial 15 – 20 minutes of the 100-minute session are reserved for planning their simulations and presentations. The following materials are available to them:

1) One party-size pack of multi-colored M&Ms for up to 20 students.
2) Three cookie sheets (baking trays).
3) They can also use themselves as props to "act" any modes if needed.

While they are planning, I walk amongst them and answer any questions they may have. Often questions pertain to the difficulty of simulating convection and radiation using M&Ms. This is

where I encourage them to think more abstractly – that the representations need not be exact rather need to convey the ideas. I steer them towards techniques of theater, as in they can use their bodies, voice, and movement to convey ideas that cannot be captured with discrete static M&Ms [12].

There are three stations – solid, liquid, and gas. Each team takes one station and has 20 minutes to present their simulations. I, along with the non-presenting students, walk to the station of the presenting team. We ask questions. While the presentations are ongoing, I jot down important points on the board followed by an explanation if needed. This way we interactively complete the matrix comprising Conduction, Convection, and Radiation as one dimension, and Solid, Liquid, and Gas as the other dimension on the board *c.f.* Figure 1.

Students are also asked to document their presentations using photographs and videos and include those in their reflections.

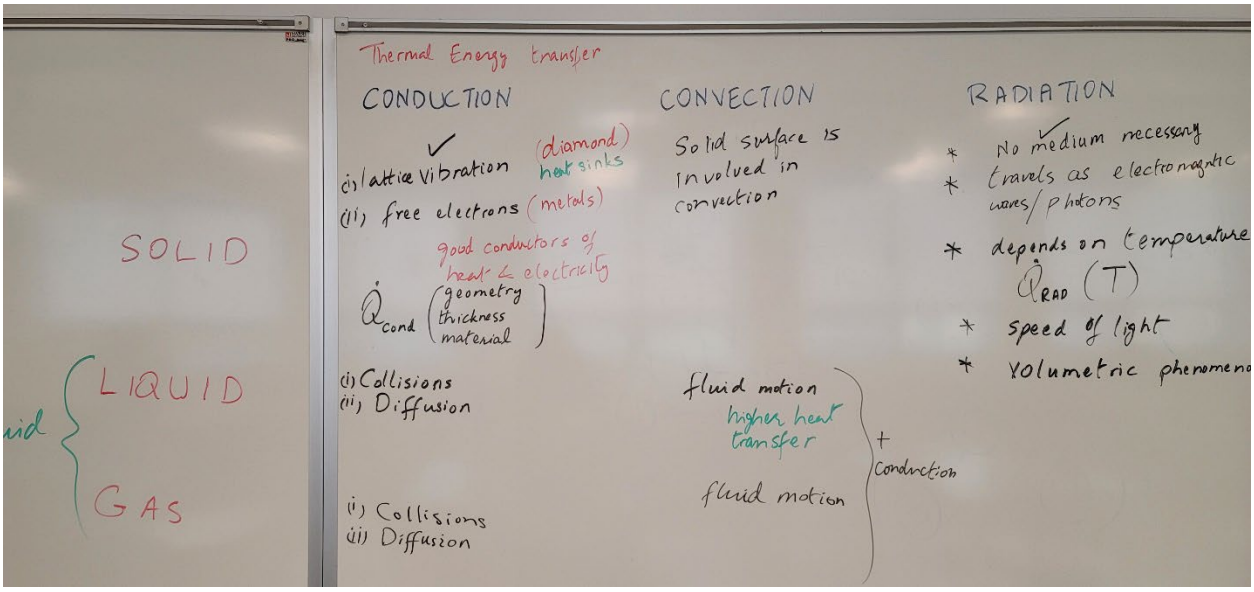


Figure 1: Information jot on the board during student presentations.

Post-activity:

Students submit their reflections on, *"How did this activity help, or did not help, you understand the mechanisms of heat transfer (conduction, convection, radiation) in solid, liquid, and gas states?"*

Scaling it to larger class sizes:

Pre- and post-activity assignments remain the same. In-class laboratory session can be organized by assigning each phase (solid, liquid, gas) to multiple teams. It is important that the team size not exceed 4 students to keep all students engaged and have a significant role to play. With more

than one team working on the same phase, it would be interesting to see varying representations of the same phenomena. Faculty can highlight the diversity of thought in interpreting and representing the same phenomenon in the post-activity debrief. This would also provide an opportunity to normalize how different people learn in different ways. If the number of teams is too large to fit the walk-through in one laboratory session, faculty can choose one or two teams for each phase to present to the whole class. The faculty can ask if any other team discussed points that have not been presented yet. This gives every team an opportunity to share the highlights of their work while also appreciating the need for succinct presentations. It makes the discussion lively and engaging. The main learning that happens is through students thinking, planning, and executing representations. If they do not know which team would be selected to present, they will all work to prepare a quality presentation.

Representations:

In our curriculum, this is the very first time they study heat transfer. This exercise is their very first introduction to Heat Transfer. Below I shall present their simulations described in their own words. The reader can appreciate that they are working out concepts in their mind as they create representations. This constructivist approach allowed them to ask questions pertaining to how to translate one abstraction (microstructural phenomena) to another (M&M representation). In doing so, they engaged with the concepts more deeply. Notice how they are pointing to the difficulty of representing some modes and are constantly going back and forth between abstract concept and physical objects, which forms the basis of scientific reasoning [7].

Solid

"Our group decided to use our M&Ms to describe a campfire with three tents nearby. The campfire, in orange, gives off thermal radiation to the main tent, yellow and green. The green tent right next to the main tent uses conduction to heat up. The blue represents wind carrying heat, the red M&Ms, to the brown tent via convection."

"My group (solids) did it entirely differently then the others creating a color coordinated example that showed all three modes in one go. While the other groups portrayed the interaction between molecules using the M&M's as the molecules/photons/atoms/waves. Being the solid team, we chose to represent different solids and use colors to portray atoms moving although I wish we could have somehow incorporated movement into out example."

"...we were able to combine the three mechanisms of heat transfer into one scenario and it helped to be able to apply the concepts to the M&Ms on our sheet to show and explain conduction, convection and radiation. The picture of our sheet might look like a big mess of random M&Ms, but we had each color represent a specific part of our scenario which helped when it came time to explain to the class our thoughts. Our solid bodies were shown in a lattice structure of a 4x4 or 6x4 M&M structure. We displayed conduction via free electron transfer,

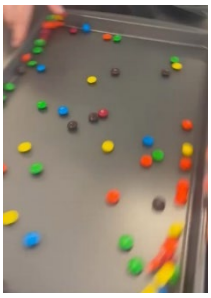
convection via natural convection from the wind, and radiation from the fire below our solid bodies."

Liquid

Conduction

"The first simulation was for conduction. In a liquid, molecules are energized as a result of being heated. Those energized molecules collide with other molecules causing them to become more energized. A chain effect happens and eventually all molecules will be energized, meaning that heat has transferred throughout the system. To simulate this, we shook the M&Ms on the baking sheet to show the colliding and thus heat transfer. This is difficult to show in a photo, so I have not included one."

Convection



"Convection with a liquid involves some sort of solid boundary or medium. The liquid passes over the solid and that is where heat transfer occurs. A way to visualize this is by a cup of coffee. When you pour it into a mug, heat transfer occurs even when the liquid sits still, but if you swirl the coffee in the mug the liquid passes over the sides making the heat transfer quicker. Using M&Ms we showed that the molecules are excited and transfer heat to the mug, but when the baking sheet was spun about a point, the M&Ms moved to the outside of the baking sheet, meaning heat is transferred to the mug after flowing over it. Pictures are included below, the top being before the simulation and the bottom being after."

Radiation

"The third mode of heat transfer is radiation. Radiation uses electromagnetic waves and photons traveling at the speed of light causing the molecules of liquid to be excited as heat transfer occurs. The effect of excited molecules is very similar to the effect conduction has, where the molecules bounce off one another. The way we showed this with M&Ms is by having one group of M&Ms at one end of the tray and another at the other end. One by one, we flicked the photons to the larger group of molecules which caused the molecules in the large group to move. This simulates the excitement of the molecules and is meant to show photons from the sun hitting a large body of water like the ocean. This is also difficult to show in photos, so I hope my explanation was thorough enough."

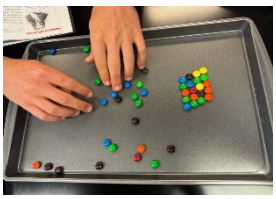
Gas

Conduction

"...in conduction, heat transfer in gasses is transferred through diffusion and collision of molecules."

Convection

"For convention in gasses, the heat is transferred through diffusion and collision. To represent this with the candies, the team showed a square molecule that had other molecules diffusing throughout and around the particle."



Radiation

"For radiation, our team portrayed electromagnetic waves, since no medium is required for the heat to travel, as the molecules (candies) sporadically moved on the baking tray as shown below."

"First Figure: Radiation of a Gas – Electromagnetic wave moves in. Second Figure: Radiation of a Gas – Electron pushed to other molecular structure."

Reflections:

The following themes emerged in student reflections:

(1) Deconstructing heat transfer: Since this is their first formal introduction to Heat Transfer, they brought a very simplistic understanding of heat transfer to class. Below they demonstrate how this work steered them towards understanding the mechanisms of heat transfer.

"Before the activity and the reading, I never thought that conduction, convection, and radiation were so different and more complex than just heat from one object or source moving into another."

"When studying solids, liquids, and gasses, I had originally thought the three methods of heat transfer to be restricted to only one state of matter. For example, solid only can conduct, etc. While this was clearly not the case. M&M's showed me that multiple phases of matter can be included in on one heat transfer method, such as radiation and convection."

"Seeing how convection does not apply to solids was very interesting to me because I had never thought through the idea before."

"After our lab session using the M&Ms, I have a better understanding of conduction as it relates to solids. I now know that there are two different forms of conduction, lattice vibrations and free electrons. Lattice vibrations, which is typical in diamonds, is when the atoms of a solid transfer thermal energy to another solid. This is utilized in heat sinks to

cool off electronics. Free electrons, used in metals, is the heat transfer via electrons. This is best used wires."

"This activity helped me understand more about the mechanisms of heat transfer because it gave me a visual representation for how conduction, convection, and radiation take place. From this lab I learned that with solids, they can conduct through lattice vibrations which frees electrons to travel to different objects. Solids cannot have convection without a fluid whether that's liquid or gas. When it comes to solids and heat transfer the three properties that are most important are the geometry, thickness, and material. This will help determine how well the solid is at conducting. For liquids I learned that conduction occurs when there is collisions and diffusions. The same goes with gases. Similarly, convection for fluids works the same and there is usually a higher heat transfer during convection. When it comes to radiation, there is no medium necessary, travels as waves usually at the speed oflight and it depends on temperature."

(2) Hands-on minds-on learning: Below they are providing evidence for how combining representations, movement, and oral commentary helped them engage with the material and retain concepts.

"… reading gave me good baseline knowledge of these modes but for me I learn the best when I can engage and apply the concepts that we read about inside the lab. I'm a very visual learner. No matter how many times I read about certain concepts or theories I never truly grasp the knowledge until I put it into action before my own eyes. Being able to use M&M's inside our groups to talk about each mode and come up with a visual representation of each really helped solidify the concepts and knowledge in my head."

"I'm a hands-on learner so being able to get into the lab with an interactive lab really helped me solidify these concepts."

"While the reading was helpful in learning these general topics, the lab allowed for a better visual and some real-life examples of these topics."

"When understanding the three concepts of conduction, convection, and radiation I think it was necessary to do some sort of hands-on demonstration and explanation to fully grasp the concepts that the book explained. When reading the textbook, I felt I had the basics of what would be discussed in lab down but by seeing it explained using the M&Ms it helped to solidify the concepts. …Overall, combining the reading with the in-class application helped me to fully understand the concepts better than if I had only read the chapters or only done the in class activity."

"Personally, I am a visual and hands on learner so doing an activity like this really engages my brain. With my brain being engaged it makes me want to learn and helps me develop a deeper understanding of the material rather than just reading from the

textbook. Reading from the textbook does work for me in understanding the concepts and material although it does not sink in entirely by just doing the reading and looking through examples"

"My reading was admittedly very shoddy, essentially just a quick skim through the relevant material. During this skim I attempted to find information that seemed relevant to our current situation; Specifically, the three methods of heat transfer. Compared to that rather nonchalant approach, the exploration in class was much more thought provoking. This was primarily due to the exploration of each example after it was demonstrated, by exploring each example and building the table with the class I felt like I was more closely tied to the results that were presented. Also, I didn't entirely realize how convection worked and why it was a bit odd to try and describe it within a solid, so getting to discuss it was rather useful."

(3) The role of abstraction in deepening understanding: Below they refer to the challenges and limitations of using a simplistic model (M&Ms) to represent more complex phenomena. This is where they are led to engage in abstract thinking.

"In the lab we were assigned creating representations of each mode (conduction, convection, radiation) with the gas phase of matter. When making these representations we ran into a few questions. The first question was how do we represent a gas with M&M's when gas molecules are super scattered and moving around at very fast speeds? To answer this we came to the conclusion that it would be very difficult to represent the gas particles with M&M's so as a group we decided to just represent the gas as more of a normal molecule but emphasize the speed and randomness of a gas when we would present our representations."

"Looking back on the representations we were able to represent conduction and convection easily since conduction for a gas just relies on collisions and diffusion. Likewise, convection of a gas just relies on conduction plus fluid motion with a solid surface involved. The representation that was the hardest for us was radiation. Radiation was difficult because it's due to the interaction with electromagnetic waves and photons. These interactions happen at the speed of light. So, we asked as a group how we would represent two things that travel at super high speeds, gas and radiation? Again, we just tried to make it as simple as possible by creating an electromagnetic wave interacting with gas molecules. It's impossible to represent the movement of these two things because they move at incredible speeds. We just ensured that we would make sure to emphasize the speed at which these things interact with each other when we presented our representation."

"Some of the mechanisms were harder to show than others, mainly the radiation process. This is because this method of heat transfer is usually instantaneous (at the speed of light) and occurs at the atomic and electron level."

(4) Collaborative learning ensues from a wide range of representations: This work allowed students to appreciate how diversity of thought and action is an asset. They engaged with each other's work and learnt.

"I found it very interesting how the different groups chose to portray their examples. My group (solids) did it entirely differently then the others creating a color coordinated example that showed all three modes in one go. While the other groups portrayed the interaction between molecules using the M&M's as the molecules/photons/atoms/waves. Being the solid team, we chose to represent different solids and use colors to portray atoms moving although I wish we could have somehow incorporated movement into out example."

"It was also interesting to hear and see how the other groups interpreted and displayed their forms of heat transfer with their models of M&Ms, this in turn helped contribute to the overall understanding of the lab."

(5) Comparative thinking: This work allowed them to engage with higher order thinking on Bloom's Taxonomy by comparing and contrasting various scenarios.

"… the group was given the task of using M&Ms to demonstrate the differences and similarities between these terms. A class discussion followed that allowed an even greater understanding of the how these relationships change between solids, liquids, and gases."

"The M&M activity completed in lab was very helpful to visualize different mechanisms of heat transfer in solid, liquid, and gas states. From reading the text, it was hard to understand situations where the modes of heat transfer would apply, but by utilizing the candies with different theoretical situations, helped to fully understand what the text was trying to portray."

"I believe that I have acquired a good understanding of the similarities and differences of the three forms of heat transfer."

(6) Connections building: Further up in Bloom's Taxonomy building connections helps them analyze.

"… helped me make connections from prior classes that I had not thought to apply to this concept."

"… going through each table's examples with the M&M's and then making connections and writing them down on the board was very beneficial for me."

Limitations of the study and future work:

In this paper, I intend to share with engineering educators the planning and execution of an exercise that I have devised in response to my challenges in keeping students engaged and motivated in a subject matter that they have repeatedly termed as “dry.” I devised this exercise through my *observation* of student approaches, behaviors, and performance; *reflection* on student feedback; and *reading* a wide array of subjects over the course of many years. The data sample is limited. It comprises only my students, albeit over the course of a decade. A quantitative measure of pre- and post-exercise student performance is not recorded as my primary concern is the benefit that my students receive by including this exercise in my teaching techniques. At this point in time, the statement of benefit draws from my observations of student engagement student attitudes recorded in course evaluations. A more thorough quantitative study may be designed in future by comparing with a control group that does not receive the benefit of this technique.

Concluding remarks:

Applying hands-on minds-on approach at the introductory level of the study of heat transfer, helped students move to higher levels of Blooms taxonomy. Reading keeps them at the first two levels (Recall and Understand) at best. Using this muti-modal approach (reading, planning, performing, explaining) contributed to deeper learning as it took them to the third and fourth levels (Apply and Analyze) by building connections. This higher-order thinking was evident in their work throughout the semester as we explored these modes of heat transfer (conduction, convection, and radiation) mathematically and experimentally.

This was also good exercise in appreciating the role of diverse ways of thinking and presenting. Faculty often struggle with encouraging students to embrace diversity. This was a good show-not-tell way of demonstrating how different people’s interpretations contribute to overall understanding.

This simple technique draws on powerful theories from the disciplines of Education, Psychology, Neuroscience, Art and Theater and yet can be implemented rather easily. The materials involved are minimal and inexpensive. The time investment on part of faculty is also minimal. The time invested in developing and executing this exercise pays off throughout the semester as students are more engaged, more interested, and perform higher-quality work. This can be scaled to large class sizes as well by having multiple teams work on each phase of matter.

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