Conservation: The Thermodynamics of Sustainability

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Overview

Physics, in some respects, is the easiest science to teach at the high school level because it benefits from an enormous number of real world applications. Connecting mechanics and even E&M to real world observations and engineering projects is natural, but what about elementary thermodynamics? With the global focus on climate, energy and sustainability, an intuitive understanding of thermodynamics is becoming more and more important for students to be able to participate in modern scientific discussion at any level.

This unit focuses on heat. Students will develop the idea that heat is energy. In addition, they will study the three mechanisms for heat transfer. Their eventual goal is to cultivate this understanding to the point where they can apply it to two different real life scenarios. The first is a major product assessment where students will develop an insulated travel coffee mug using their understanding of heat transfer. The second is using their understanding of energy conservation to recognize and deconstruct pseudoscientific literature and debunk unsupported claims about heat and energy.

Rationale

For students to really interface with science, they should be doing science. When they can make observations, analyze data and make generalizations and predictions based upon that, they're better able to articulate their understanding and make informed and well supported arguments. Beyond that, students should be able to use their understanding of physical principles to solve real world problems. The focus of the unit, then, will be to take the study of thermodynamics, contextualize it and make students interact with it directly.

Physics is often viewed as “too hard” for general study, to the point that it’s not even a required class in most high schools or colleges. This is doing our students an intense disservice, both by limiting their understanding of the world and also by limiting their potential career options. Richard Muller says, “Physics is the liberal arts of high technology. Understand physics, and you will never again be intimidated by technological advances.” Physics gives those who study it a powerful toolkit by which they can ask questions, find their own answers, understand problems and interpret their own world.

Teaching students in an urban public school is all about empowering them to take control in their lives when they feel they have none. To that end, I view physics as a foundational topic, like arithmetic or literacy. It forms the basis of processing observation, generalizing patterns and understanding the world around you. There’s nothing more exciting than the moment when a student first realizes that a little bit of physics goes a long way in deconstructing the black boxes of technology that are pervasive in our world. The shroud of mystery that surrounds cars, televisions and cellphones just falls away and the true nature of complex systems reveals itself: Everything in the universe is just a collection of simpler stuff all stuck together, understand the pieces and you can understand the whole.

When I’m asked what students should major in as undergraduates, my stock response is physics. They think I’m joking until I break it down for them. You don’t need to be a physicist, professor or teacher if you study physics. The analytical skills and systematic worldview that is cultivated in studying physics is highly desirable in the fields of engineering, medicine, finance and economics (to name a few). Studying physics is challenging, but gives you the tools you need to confidently say, “I don’t know what to do, but I can figure it out.” What’s more empowering than that?

Objectives

This unit is designed for 11th grade students currently enrolled in a physics course meeting five days per week for 48 minutes at a time. The initial unit will be designed for a class of Advanced Physics students, but will scale easily for students enrolled in AP Physics 2.

The content objectives for the unit revolve around heat, energy and efficiency. Students will, over the course of the unit, be able to identify heat as a form of energy and link temperature to mechanical energy. They will observe and identify the mechanisms of heat transfer and then quantify these heat flows. Students will also apply energy conservation to thermodynamic systems, realizing that energy has to go somewhere and typically, energy that appears to have been lost just manifests itself elsewhere as heat. To tie this all back to real problems, students will develop a concrete understanding of efficiency in systems. They'll observe and quantify this efficiency and use what they know to answer modern questions about energy. Some of the topics they'll cover include alternative energy sources, the energy needs of the world and devices of dubious plausibility.

The skill objectives students will meet are varied, but are typical for a high school physics course. Students will learn problem solving and estimation techniques. Students will improve their ability to make arguments that are supported with evidence and data. Students will learn to use temperature probes to gather data and how to use Excel and LoggerPro to graph and interpret that data. Finally, students will learn about iterative engineering design cycles and how to apply knowledge to solve real-world problems through engineering and design.

Strategies

The flow of educational strategies will start with inquiry-based activities to establish a foundation of knowledge that students will create themselves. Students will be asked to develop their own questions, design their own tests and report their own results. This provides ownership and control over their own learning, as well as helps them to develop effective communication skills.

Students also will need to interpret and understand data in order to be successful in science. In this unit, encourage them to graph everything and then take a step back and explain what the graph is telling them. Once they can verbalize that, then have them use that data to support arguments. Whether they're pitching a product, debunking a myth or explaining their point of view, an argument that's supported with evidence is always stronger. They can also use these skills to be critical of the things they read. In this unit, students will be writing, presenting and explaining. Be sure to hold them accountable for using evidence to support everything they say.

The final strategy is teaching students that engineering is an iterative process. Solving problems can be seen as a constant cycle of trying and refining their work and checking that the decisions they make are consistent with their understanding. Sometimes the best way to make progress is to just dive right in and try something to get an idea of how something might work. Once they go through a few design iterations, they'll use the data analysis skills and communication skills they've already developed to present their work to other people and justify their claims with evidence.

Classroom Activities

Day One: Introduction to Heat and Temperature

For the first day, students should focus on collecting prior knowledge and organizing ideas. The discussions should be fully student centered with the teacher serving as facilitator.

Activity One: Collecting Prior Knowledge

The first activity on the first day is designed to help students unpack all of their preconceived notions about heat, temperature and energy. You'll want to put students into six or seven small groups of about 3-5. Give each group a card with a single word – for six groups, use heat, temperature, efficiency, conduction, convection and radiation. If you have seven groups, add a card for "energy." There's a chance that students might not have any exposure to convection, so be ready to swap their card for either energy or calorie and save convection for a whole class discussion. Give students ten minutes to create and hang posters with drawings, words and/or mind maps that relate to their word.

Once the posters are up, give students five minutes to circulate around the room and add ideas and connections to the other groups' posters. If they're being productive, extend the time slightly. When it's over, collect students together and have a representative from each group summarize the ideas listed about their topic. Be sure to leave ample space for student discussion and interaction between the different groups.

Activity Two: Developing Vocabulary and Organizing Ideas

To start, have students rub their hands together and then describe what happens. Coax out of them that friction causes their hands to feel warmer and that there is a connection between work, energy and temperature. To drive this point home, put some water into a high powered blender and add a temperature probe. Run the blender and plot the temperature of water vs. time for students. Feel free to add an electrical power meter to show energy delivered to the blender vs. time to further demonstrate the transfers of energy.

Once students get to a place where they understand heat is a form of energy and that temperature is related to kinetic energy of molecules, begin to discuss transfers of energy. Students should already have a pretty good idea of what conduction, convection and radiation are, even if they're not familiar with the terms. End the discussion with some "official" definitions of the words you started with.

At this point, it's important to introduce the "official" Laws of Thermodynamics. For a course of this level, the Zeroth and First Laws are mandatory, with some discussion of entropy and the Second Law being left up to you. I prefer to do it, because I think it illustrates some important ideas that can spark some higher level thinking in some students, even though it can feel esoteric. I don't discuss the Third Law of

Thermodynamics at all. For most students, it seems to help to think about the first two laws in terms attributed to Allen Ginsberg. He cleverly restated the first law as, "You can't win" and the second as, "You can't break even." The really important takeaways for students are that energy is conserved and some of the limitations on how heat can be transformed back into mechanical work.

Days Two – Four: Investigating Heat Transfer

For three days, students will take the terms that they learned and explore them as concepts. Students will divide up the different heat transfer mechanisms, perform background research on them, design investigations and then present their results in a poster-talk format.

Activity One: Research and Development (One Day)

Divide students into groups and assign each group a heat transfer mechanism. Students will spend the first day conducting research on what the mechanism is and then design an investigation that results in a temperature vs. time curve in LoggerPro. Some examples of investigations students might come up include: the effect of type or amount of material on rate of conduction, the effect of air flow velocities on convection, the effect of lid design on fluid cooling, the effect of color on cooling, the effect of color on radiation absorption, the effect of type of light source on rate of heating.

Feel free to assist students in crafting their ideas, but make sure to let students pursue their ideas. Results that don't pan out will still provide valuable information. At the end of the first day, students should submit a materials list and a skeleton procedure to be carried out on the following day.

Activity Two: Experimentation (One Day)

On the second day, students should be carrying out their experiments. If possible, they should generate computer graphs in LoggerPro using electronic temperature sensors. If that's not possible due to financial constraints, data can be taken with thermometers and stopwatches. That data can then be transcribed into LoggerPro or Excel to generate graphs.

Students should complete their experiments in class and develop their graphs for homework. What students should prepare for the next day is a poster that outlines the background information, methodology, results, analysis and error analysis for their investigation. Students will be expected to give a short talk of approximately five minutes during the next day summarizing their results.

Activity Three: Reporting and Discussion (One Day)

Students will take around 5 minutes to defend their results and methodology. Ask them probing questions to explore their understanding of sources of error. Students should be evaluated on the five sections of the poster (background, methodology, results, analysis and error analysis), how they communicate those results and their understanding of them. After each group has presented, generalize their results as a class and provide students with clear definitions and descriptions of convection, conduction and radiation as heat transfer mechanisms.

Days Five – Seven: Busting Temperature Myths

Activity One: Research and Development (One Day)

By this point, students will have probably asked some questions or put forth some ideas about temperature. The next activity is for students to deconstruct some of these myths and reconcile them with their new knowledge. The first day will be spent by students researching these ideas and myths as well as developing systematic ways to test them. Some examples of myths students might come up with include: the effectiveness of blowing on food to cool it down, when to put milk into coffee in order to keep it hot, how to place fans in order to keep a room cool, most body heat is lost through the head or you should wear light colors to keep cool in the summer. If this is the fifth day and the unit began on a Monday, students will have the weekend to gather whatever materials they might need to conduct their investigation.

Activity Two: Experimentation (One Day)

As with the previous activity, on the second day students should carry out their investigation. They will need to generate whatever graphs or visualizations required to demonstrate their point. As before, students will prepare a poster that outlines the background information, methodology, results, analysis and error analysis for their investigation and give a talk about their work the following day.

Activity Three: Reporting and Discussion (One Day)

Students will take around five minutes to present their myth, provide background, describe the tests they performed and summarize their results. Other students can ask a few questions to each group. Students should be assessed on methodology and their ability to connect what they discovered back to what they know about temperature, energy and heat transfer.

Day Eight: Pondering Questions

A great way to tie together conceptual understanding and literacy skills is by having debates. Since physics debates are different than similar activities in other classes, it's important to be mindful of the format. Devote time to teaching it so that students are clear about the expectations. In addition, I'd highly suggest posting the steps for the debate on a board or poster so that students can refer to it during the activity.

Format

Assign each question to a group or person on the day you want to discuss them. When it's time to discuss a question, the group who is presenting it is in charge of leading the discussion on that question. Their first task is to read the question and confirm that everyone understands what it's asking. I encourage students to call on another student to explain the question in their own words. After, the group leading the discussion should provide their answer with no explanation whatsoever. Have them write it on the board. Then, they should solicit other answers (still with no explanation) and write them on the board as well. Number the theories and have students take turns explaining, supporting or refuting theories. This must continue until everyone in the room is compelled by logic or example. The hardest part is waiting to make sure everyone is convinced. If the discussion stalls, feel free to offer up new theories to either lead the students to or from obvious faults in their logic. If there's no way everyone will agree, then students should design an experiment to settle the argument and then carry it out. At that point, once they've observed the right answer, they can backtrack and explain it.

It's important that students have a chance to see and think about the questions in advance. Handing them out three days before you plan on discussing them is highly recommended. It's important that they realize they're not being evaluated on their answer, but instead on their participation in (and contribution to) the class dialogue. This is tough for kids to get used to, especially because no one likes to be wrong. Resist the urge to guide the discussion to the answer you want, as well – it's important that the kids really hash this out on their own. Example questions can be found in the Appendix.

Days Nine – Thirteen: Build a Better Coffee Mug

For their major assessment, students will engineer a travel coffee mug. Doing so effectively requires them to take their knowledge of heat transfer and put it directly into practice. In addition, they should take some of the data and understanding out of the activities from days two through four as a starting point for their research and construction.

Part One: Design Parameters

Any good engineering project starts with a problem and some basic parameters. For this one, students are to build a reusable coffee mug that must be able to be carried around and used at school. It must be washable and reusable. It has to hold 12-16 oz. of coffee and the user must also be able to drink from it directly.

Part Two: Evaluation Criteria

Students will treat this as a bid for a contract where they are developing a luxury product that is evaluated on pure performance. Teams will be required to present posters that show cooling curves and justify their design choices with thermodynamic principles. The highest grades go to the teams with the best combination of performance and justification. Similar to any other activities done in this unit, any claims made must be backed up with evidence. In an effort to sweeten the deal and add a little extra motivation, I'd agree to use the winning design as my personal in-class coffee mug for the year.

Days Fourteen – Fifteen: Wrap Up and Contextualize

At the end of the unit, it's important to wrap up all of the major topics and extend what students have been discussing into some more pressing political issues. One of the big places that thermodynamics is relevant is in the world of climate science. In the last two days, students will explore climate change mechanisms and put their knowledge to use evaluating some of the pseudoscientific literature on the subject.

Activity One: Major Topic Overview

Ask students what they think the big ideas were. If they talk about how heat is transferred and mention something about how energy is conserved, it went well. Now is a great time to revisit the Laws of Thermodynamics, the big ideas in heat transfer and spend another few minutes heaping praise upon whatever group did the best job designing the coffee mug. This should only take maybe 10-15 minutes total.

Activity Two: How is Thermodynamics Relevant?

Propose to the class two questions: Carbon Dioxide in the atmosphere absorbs some of the infrared radiation that is radiated by the Earth. If this CO_2 then radiates the infrared radiation that has absorbed, what effect might this have on the Earth? If burning fossil fuels ejects small particles of black soot into the air, what effect might that have on the Earth? If students need a hint, remind them you've been discussing thermodynamics and heat transfer.

Understanding heating and cooling mechanisms is one key to understanding the future of our planet and lays the foundation for understanding a big chunk of climate science. Students should be able to pretty easily come up with the idea that black soot will absorb more radiation and make things warmer. The greenhouse effect might be a little more challenging, but a diagram and the idea that radiation happens in all directions should get them to where they need to be. From there, negative impacts like sea level rise and ice melting can be explored through video, articles or other activities.

Activity Three: Alternative Energy and Debunking Pseudoscientific Literature

The final activity for the unit involves students revisiting the Laws of Thermodynamics and taking the concept of efficiency to read and evaluate some articles or claims about solar energy, wind energy, climate change denial, water powered cars, perpetual motion machines and any other dubious science you can dig up. A few examples of pseudoscientific "literature" can be found in the student resources section. To maximize class time, read one short claim and rebut it together. I'd suggest the "Magnets 4 Energy" site as a great place to start. After students see what they're looking for, have individual groups answer a question on a poster sized piece of paper to explain to the rest of the class. Then facilitate a discussion afterward.

The big issue students will have relates to their ability to use evidence to challenge authority. I've found that if my students read something that sounds plausible, they'll tend to believe it only because it "sounds right." The skill you're trying to cultivate in them here is fact checking and trusting their experience and physical intuition. The more comfortable they can become in supporting their ideas with evidence and applying knowledge to evaluate an argument, the more effective thinkers, writers and citizens they will become.

Endnotes

A huge emphasis has been placed on semiformal communication of ideas. Instead of the traditional "lab report," students should be prepared to discuss and defend their ideas in front of peers. While this will be intimidating for them at first, it aligns heavily with the Next Generation Science Standards and Common Core standards, as well as places our students in a strong position to not only do science, but also communicate about their process, forcing them to better understand their own work.

Care has been taken to balance inquiry, engineering, argumentation and current events to supply a well rounded treatment of thermodynamics that leaves a lot of room for students to develop and pursue their own ideas and passions. It's important that students appreciate that science and engineering are inherently creative professions and provide them with tools that make them well rounded, regardless of what educational or career path they follow.

Annotated Bibliography/Resources

Reading List

Feynman, Richard P. *The Feynman Lectures on Physics, boxed set: The New Millenium Edition.* Basic Books, 2011.

In my eyes, Feynman was the greatest physics educator that ever lived. The Feynman Lectures were designed for incoming Freshmen at CalTech and cover a vast array of topics from mechanics, to thermodynamics, to relativity to quantum mechanics. Before I teach any topic, I like to see what Feynman said about it. His insights and explanations are truly beautiful and are what inspired me to become an educator.

Muller, Richard A. *Physics and Technology for Future Presidents: An Introduction to the Essential Physics Every World Leader Needs to Know.* Princeton University Press, 2010.

This is the best conceptual physics textbook I've ever seen. It was recommended to me by my seminar leader and was an excellent suggestion. It's fairly light on calculation, fun to read and incredibly useful. If I were able to, I'd compel my principal to order a set and redesign the conceptual physics classes in our school around it. It'll provide, for this unit, very intuitive descriptions and examples of thermodynamic concepts in ways that will be accessible and understandable to students.

Teacher Resources

Feynman, Richard P. *Exercises for The Feynman Lectures on Physics.* Basic Books, 2014.

A good chunk of problems that correlate with the Feynman Lectures on physics. Some of them are challenging for undergraduates, but the questions are asked in a way that makes them significantly more thought provoking than a traditional physics problem. Each section carries a balance of conceptual and computational questions designed to really stretch the understanding of an idea.

PhET: Free Online Physics Simulations. < https://phet.colorado.edu/ >

If you don't have access to some lab materials, PhET is an amazing repository of online physics experiments run by the University of Colorado. Students can play, explore and take data on a ton of different topics.

Student Resources

Busting Myths: A Practical Guide to Countering Science Denial. <http://www.skepticalscience.com/Busting-myths-practical-guide-countering-science-denial.html>

A legitimate resource that highlights for students the red flags thrown by pseudoscientific literature and how to effectively replace those ideas with actual evidence in the minds of people who defend them.

Magnets 4 Energy. < http://magnets4energy.com/>

A classic "Free Energy" scam site. This is incredibly typical of the types of scams that have been running on the internet for decades. Students should be noticing that there's no attempt to prove or demonstrate devices, only an attempt to sell something that sounds too good to be true.

Multiple Scientists Confirm the Reality of Free Energy – Here's the Proof. < http://www.collective-evolution.com/2013/10/11/multiple-scientists-confirm-the-reality-of-free-energy-heres-the-proof/>

This is an article where multiple scientists appear to confirm the existence of free energy devices and technology. I'd highly recommend editing out the parts about UFOs before you presented anything you found here to students.

Open Source Plans for Modern Tesla Free Energy Generator Released to Public. < http://www.wakingtimes.com/2014/04/14/open-source-plans-modern-tesla-free-energy-generator-released/>

Open source plans for a free energy generator. The fact that it's free should add to the credibility (especially when compared to the magnets4energy site), but students should be investigating the energy transfers – how does energy go in? How do you get energy out? How much does it claim to generate compared to what it takes in?

Practical Guide to Free-Energy Devices. <http://www.free-energy-info.com/>

This is a repository of "Free Energy" information with multiple different types of devices and resources.

The "Greenhouse Effect" Hypothesis. < http://www.spinonthat.com/CO2.html >

This is an extremely poorly written attempt to debunk the greenhouse effect. It contains a fair amount of simple numbers and an experiment, which may throw some students off, but they should be able to pick through and find all of the junk.

Classroom Materials

LoggerPro

LoggerPro is a software package from Vernier that records and analyzes data. I'd highly recommend it because of their irrationally generous site license. If you buy one copy of the software, you can install it on every computer in your school, every computer owned by a teacher in your school and every computer owned by a student in your school. Plus you get free updates. For scientific work, I find it to be much more powerful than Excel because it comes with much better curve fitting packages and the ability to automatically compute (and graph) derivatives and integrals.

Vernier Temperature Sensors

Vernier is my preferred manufacturer of classroom data logging equipment. They make a ton of different temperature sensors, but I'll only recommend two of them. If you haven't already invested in a whole Vernier hardware package, the Go!Temp is great. They're around $40 each and plug directly into a USB port of a computer or other device to transmit data to LoggerPro. If your school uses iPads, iPhones, Android devices or is a BYOD school, Vernier also sells a Bluetooth temperature probe called the Go Wireless Temp for $75. It's a little more expensive, but offers a bit more flexibility and a much higher "coolness" factor.

Appendix

Activity Materials

Ponder Questions

Why does the Earth cool more quickly on a clear night than a cloudy night?
What happens to the work done on a can of juice when it is vigorously shaken?
Why does the water in a metal canteen stay cooler if the cloth jacket surrounding it is kept moist?
Can you warm a kitchen in winter by leaving the oven door open? Can you cool the kitchen on a hot summer day by leaving the refrigerator door open?
The oceans contain a tremendous amount of thermal energy. Why, in general, is it not possible to put this energy to useful work?
Living organisms convert simple food molecules to complex structures as they grow. Is this a violation of the Second Law of Thermodynamics?

An inventor brings you an "in room air conditioner." It's a giant box that is placed in the middle of a room and, when switched on, provides a stream of cold air. What's the problem?

Next Generation Science Standards

Many states have already adopted the Next Generation Science Standards, which are organized based upon a number of different practices. This unit directly addresses the following standards"

- Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena and solve design problems, taking into account possible unanticipated effects.
- Design, evaluate, and/or refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations.
- Compare and evaluate competing arguments or design solutions in light of currently accepted explanations, new evidence, limitations (e.g., trade-offs), constraints, and ethical issues.
- Evaluate competing design solutions to a real-world problem based on scientific ideas and principles, jointly developed and agreed-upon design criteria, empirical evidence, and/or logical arguments regarding relevant factors (e.g. economic, societal, environmental, ethical considerations).
- Compare, integrate and evaluate sources of information presented in different media or formats (e.g., visually, quantitatively) as well as in words in order to address a scientific question or solve a problem.
- Gather, read, and evaluate scientific and/or technical information from multiple authoritative sources, assessing the evidence and
- Communicate scientific and/or technical information or ideas (e.g. about phenomena and/or the process of development and the design and performance of a proposed process or system) in multiple formats (i.e., orally, graphically, textually, mathematically).

In addition, on the topic of Reflecting on the Processes of Science and Engineering, the authors of the standards state:

> Engaging students in the practices of science and engineering outlined in this section is not sufficient for science literacy. It is also important for students to stand back and reflect on how these practices have contributed to their own development, and to the accumulation of scientific knowledge and engineering accomplishments over the ages. Accomplishing this is a matter for curriculum and instruction, rather than

standards, so specific guidelines are not provided in this document. Nonetheless, this section would not be complete without an acknowledgment that reflection is essential if students are to become aware of themselves as competent and confident learners and doers in the realms of science and engineering.

State Standards

The Philadelphia School District is making the shift to the PA Common Core set of standards. The college and career ready standards in Language and Mathematics that are supported by this unit are as follows:

Writing:

- Write informative/explanatory texts to examine and convey complex ideas and information clearly and accurately through the effective selection, organization, and analysis of content.
- Use technology, including the Internet, to produce and publish writing and to interact and collaborate with others.
- Conduct short as well as more sustained research projects based on focused questions, demonstrating understanding of the subject under investigation.
- Gather relevant information from multiple print and digital sources, assess the credibility and accuracy of each source, and integrate the information while avoiding plagiarism.
- Draw evidence from literary or informational texts to support analysis, reflection, and research.

Speaking and Listening:

- Present information, findings, and supporting evidence such that listeners can follow the line of reasoning and the organization, development, and style are appropriate to task, purpose, and audience.
- Make strategic use of digital media and visual displays of data to express information and enhance understanding of presentations.

Language:

- Acquire and use accurately a range of general academic and domain-specific words and phrases sufficient for reading, writing, speaking, and listening at the college and career readiness level; demonstrate independence in gathering vocabulary knowledge when encountering an unknown term important to comprehension or expression.

Standards of Mathematical Practice:

- Make sense of problems and persevere in solving them.
- Reason abstractly and quantitatively.
- Construct viable arguments and critique the reasoning of others.
- Use appropriate tools strategically.