The Physics Teacher

PAPERS | SEPTEMBER 01 2022

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Phys. Teach. 60, 501–503 (2022)
https://doi.org/10.1119/5.0074493

Interdependence of the First and Second Laws of Thermodynamics

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Historically, classical thermodynamics was developed during attempts to improve the efficiency of steam engines. Those investigations led to the well-known zeroth, first, and second laws of thermodynamics. Although these laws are presented independently, linkages between the zeroth and second laws have been pointed out in the physics teaching literature.[1-4] In our 2020 paper, "What if Energy Flowed from Cold to Hot? Counterfactual Thought Experiments," we imagined a universe in which energy spontaneously flowed from colder to hotter objects.[5] That paper inspired us to explore the connections between the first law and the Clausius statement of the second law in the present paper.

The main objective here is to show that the first and second laws of thermodynamics are interdependent. We begin the next section with an overview of the zeroth, first, and second laws of thermodynamics. We show why the Clausius statement is required to achieve the equilibrium states that are necessary for the first law, i.e., to achieve complete thermal equilibration to a unique equilibrium temperature. We also show that the Clausius statement requires the energy conservation part of the first law to assure that all heat processes conserve energy throughout their duration. After our main results, we have some suggestions to guide teachers on how to incorporate them into the classroom. We believe that if students understand the linkages between the first and second laws, they will have a firmer and richer grasp of thermodynamics.

The zeroth, first, and second laws of thermodynamics

***Zeroth law of thermodynamics*.** Classical thermodynamics is based on the existence of equilibrium states for homogeneous systems. For such equilibrium states, (a) no processes are in progress; (b) measurable thermodynamics variables such as the pressure P, volume V, and number of molecules N are unchanging over time; and (c) there are no net flows through the system boundaries.

In their 1939 book,[6] Fowler and Guggenheim proposed the zeroth law of thermodynamics as an appendage to the first and second laws of thermodynamics. Its intent was to clarify the concepts of thermal equilibrium when exchanges of heat energy[7] between objects are possible:

> *If object A is in thermal equilibrium with object B, and object B is separately in thermal equilibrium with object C, then objects A and C are in thermal equilibrium with one another.*

If object A is a thermometer, e.g., a constant-volume gas whose pressure is used to define temperature, then the zeroth law assures that if objects B and C are in "thermal" equilibrium with one another, they have the same temperature as object A. The word "thermal" signifies energy exchanges by heat processes. Notably, the zeroth law does not address the *approach* to equilibrium when hotter and colder objects exchange energy.

The concepts "hotter" and "colder" are not well defined until a temperature scale is defined for equilibrium states. The development of temperature scales and thermometers goes back to at least the 17th century, preceding a theoretical understanding of energy in thermodynamics. Conventionally, temperature scales are defined such that hotter objects, as indicated by human sensory perception, have higher temperatures.

First law of thermodynamics. Conservation of energy dictates that energy can be neither created nor destroyed. Students learn this first in the study of mechanics. The first law of thermodynamics is a generalized form of conservation of energy that is adapted for thermodynamic processes.

The first law applies to processes that connect initial and final equilibrium thermodynamic states, i and f. Energy can be transferred by *work* W and/or *heat* Q processes, with a change ΔU in the stored internal energy. We note that thermal interactions, i.e., heat processes, are ubiquitous, being absent only in fictitious systems with adiabatic walls.[8] The first law of thermodynamics, $\Delta U = U_f - U_i = Q + W$, accounts for these changes.[9,10] Notably, the first law contains three related ideas: (1) the existence of the internal energy function U, (2) the principle of conservation of energy, and (3) the definition of heat as energy in transit by virtue of a temperature difference.[11]

Second law of thermodynamics. To understand the implications of energy transfer by a temperature difference, we look to the Clausius statement of the second law. Clausius originally stated,[12] "Heat cannot, of itself, pass from a colder to a hotter body." He clarified that the term "of itself" was intended to cover the fact that the principle must apply to multistep processes with cycles, writing, "the principle must be applicable to processes which are a combination of several different steps, such as e.g. cyclical processes." On the same page, he then rephrased his statement as, "A passage of heat from a colder to a hotter body cannot take place without compensation."

In modern parlance, we call a cyclic device that operates without compensation, i.e., with no other effect, a *workless cyclic device*, because the net external work done on (and by) the system executing the cycle is zero.

Although Clausius did not use the term *energy* explicitly in his second law statement (which focused on "heat"), he clearly had it in mind. He was well aware of Joule's experiments on the mechanical equivalent of heat, and that *heat* passing from

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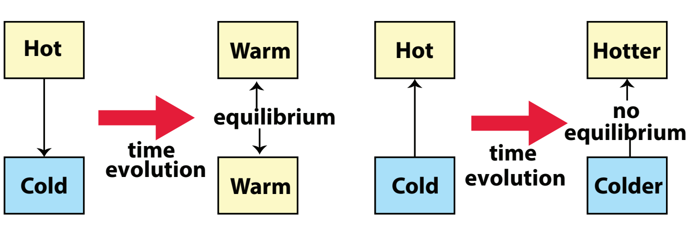

(a) Hot-to-Cold Energy Flow (b) Cold-to-Hot Energy Flow

Fig. 1. Time evolution for spontaneous energy transfers. (a) Spontaneous hot-to-cold energy transfers, with equilibration to an equal-temperature state; (b) spontaneous cold-to-hot energy transfers, with the hot object becoming hotter and the cold object becoming colder.

one body to another is energy in transit, consistent with our modern view. He introduced the internal energy function *U* into what we now call the first law of thermodynamics, which is surely a conservation law, showing that the work and heat processes on a body change its internal energy.[13]

Figure 1 shows the two possibilities for energy-conserving flows between hotter and colder objects. Part (a) symbolically indicates familiar spontaneous heat energy flow from hotter to colder objects, which heats the cooler object and cools the hotter one, until temperature equality exists.[5]

The equilibrium obtained by spontaneous hotter-to-colder energy flow is stable in that if there is a small disturbance from equilibrium, the system will return to its equilibrium state. Furthermore, temperature variations within a given object would smooth out, leading to a uniform temperature. Our everyday experience is that when hot and cold objects can exchange energy, their temperatures approach one another—which students can relate to from their own experiences.

Figure 1(b) symbolically indicates what would happen if heat energy flowed spontaneously from colder to hotter objects. The hotter object would become hotter, and the colder object would become colder. Within a given object, temperature nonuniformity would grow, and uniform temperatures would be impossible. This is contrary to our experience and is ruled out. In our universe, heat energy flows spontaneously only from hotter to colder objects.

The Clausius statement of the second law gets to the heart of thermodynamics, namely, thermal equilibration to equilibrium states. For completeness, we mention that there are two other equivalent forms of the second law. The Kelvin-Planck statement prohibits heat energy from a constant-temperature reservoir from being converted to work with no other effect [Ref. 11, p. 153]. The other is Clausius's principle of entropy increase [Ref. 11, pp. 210–213]. Both are important, and the principle of entropy increase in particular has been used widely in physics.

Main results

Our primary findings here are:

1. The first law of thermodynamics requires the Clausius statement to assure equilibration to the initial and final states *i* and *f*.

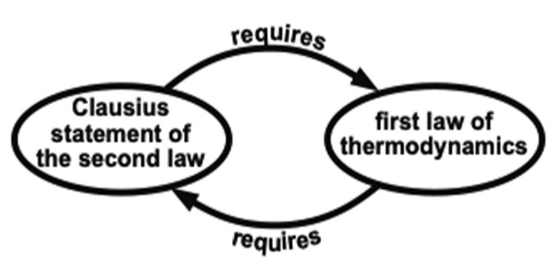

Fig. 2. Graphic view of the interdependence of the first and second laws of thermodynamics.

2. The Clausius statement requires the energy conservation part of the first law to assure that all heat processes conserve energy throughout their duration.

This is illustrated graphically in Fig. 2 and shows the main result.

• ***Key Point:*** *The first and second laws of thermodynamics are interdependent; i.e., each law requires the other.*

Instructional implications

Students might be surprised that the first law requires the second law, because the first law is often mistakenly viewed to be *only* a statement of energy conservation. Commonly overlooked is the need for the Clausius statement to guarantee that initial and final equilibrium states can be reached. Such surprises during the learning process can lead to more intense thought, and perhaps provide a spark that leads to enhanced student understanding.

For example, our 2020 paper[5] showed that if energy were to flow from colder to hotter objects, then thermodynamic equilibrium would not be obtained, temperature would not be measured, and the first law of thermodynamics would not exist. These types of insights can give students a deeper appreciation for the Clausius statement to thermodynamics.

Students should understand that human sensory perception established our understanding of hot and cold. Fire is "hot," and there is evidence for its use by *Homo erectus* humans more than one million years ago. Our experience with heating influenced the development of thermodynamics and the language we use, including the term "heat." Only later, several thousand years ago, were "cold" ice and snow harvested seasonally where possible.

Among the earliest temperature scales were two introduced c. 1700, by Isaac Newton and by Ole Romer. Both assigned higher numbers to hotter objects, as do the scales we use today. Though not widely known, some "inverted" scales have been used. An anonymous reviewer pointed out that Joseph-Nicolas Delisle's 1732 thermometer assigned water's boiling temperature to be zero, i.e., 0 °D, with higher temperatures as the water cooled. It was used in Russia for about one century.[14] Further, when developing his centigrade scale, Anders Celsius originally assigned the centigrade temperature 0 °C to water's boiling point and 100 °C for the freezing point!

Students should know that an inverted temperature scale does not imply that energy flows from colder to hotter objects.

An awareness of such scales can help students appreciate the meaning of the Clausius statement: regardless of whether a thermometer's temperature increases or decreases under heating and cooling, energy always flows naturally from hotter to colder objects as perceived by humans.

We suggest that teachers consider teaching thermodynamics by first pointing out that the first law generalizes conservation of energy as learned in mechanics, and introduces internal energy, which is stored in objects, and also heat and work energy processes that transfer energy.

It can then be emphasized that the Clausius statement requires the first law to assure that energy is conserved throughout heat processes. Since the first law of thermodynamics describes energy transfer processes between equilibrium states, the first law also relies upon the Clausius statement; i.e., the Clausius statement and first law are interdependent.

Using this approach, the first and second laws are seen to be linked parts of a pair of ***fundamental thermodynamics principles***, energy conservation and the Clausius statement. Students should appreciate the important roles of these pillars, which lead ultimately to the acknowledged primacy of energy and entropy in thermodynamics.[15-18]

Acknowledgments

Richard Kaufman is grateful to Prof. Eric Sheldon for his mentorship for 25 years since his days as a freshman in college. Eric Sheldon passed away just before receiving news of this paper.

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7. This is often referred to as "heat" or "heat transfer," which are misuses of these terms. It is well for teachers and students to realize that what is actually transferred is *energy*. That transfer can result in increased or decreased internal energy or potential energy, say of a weight on a pulley.
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13. Clausius defined the state function internal energy U as the sum of two other functions of the state of the system, the "heat in a body" H and the "internal work function" J. He argued that $U = H + J$ is determined by the thermodynamic state of the system. Remarkably, he mentioned energy conservation only four times in his 376-page book. He devoted much of his writing to the "equivalence of heat and work," which he used to express energy conservation in his famous expression of the first law.
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