Limitations and functions: Four examples of integrating thermodynamics

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Abstract

Physics students are usually unaware of the limitations and functions of related principles, and they tend to adopt “hot formulas” inappropriately. This paper introduces four real-life examples for bridging five principles, from fluids to thermodynamics, including (1) buoyant force, (2) thermal expansion, (3) the ideal-gas law, (4) the 1st law, and (5) kinetic theory. Pedagogically, the examples play the dual roles of demonstrating the limitations *(why not)* of the prior principles and highlighting the functions *(why)* of those principles that follow. Although the examples are not novel, the author enhances the pedagogical value of the existing teaching resources by means of improving visibility, addressing students' prevalent pitfalls, bridging related principles, and increasing the sophistication of the scientific reasoning.

Introduction

The literature has argued that students usually learn physics principles discretely. They tend to be unaware of the functions and limitations, i.e., the *why* and *why not*, of using individual principles, and are inclined to adopt "hot formulas" inappropriately. For example, when explaining the adiabatic compression of an ideal gas, few students can invoke the concept of "work" (i.e., the 1st Law) to justify a change in temperature (Loverude, Kautz, and Heron, 2002). When explaining processes involving temperature variation, students tend to adopt the ideal-gas law (PV=nRT) but ignore some relevant variables (Loverude, Kautz, and Heron, 2002; Rozier and Viennot, 1991). In order to help students distinguish the functions and limitations of the related theories of a physics topic, and meaningfully grasp the topic as a whole, the literature (Buncick, Betts and Horgan, 2001; Chang, 2011) has suggested developing a series of real-life examples and engaging students in thinking and discussion.

This paper introduces four examples for bridging five principles, from fluids to thermodynamics, including (1) buoyant force, (2) thermal expansion, (3) the ideal-gas law, (4) the 1st law, and (5) kinetic theory. The sequence of the five topics is fairly consistent with those which appear in undergraduate introductory textbooks. With respect to each example, both major effective theories and prevalent inappropriate reasoning are addressed. Thus, pedagogically, the examples play the dual roles of demonstrating the limitations of the prior principles and highlighting the functions of those principles that follow.

Examples and Principles

A summary of the four examples along with the corresponding theories and prevalent inappropriate theories are listed in Table 1.

Table 1: Major theories (✓) and prevalent inappropriate reasoning (×) of the real-life examples

Theories / Examples	Thermal conduction	Buoyant force	Thermal expansion	Ideal-gas Law (PM=ρRT)	The 1st law (Q+W=ΔU)	Kinetic theory $E_k \propto T$
1. Lava lamp	✓	✓	✓			
2. Hot-air balloon		✓	×	✓		
3. Atomic bomb explosion				×	✓	✓
4. Cold mountain-tops & warm foehn (chinook)				×	✓	✓

The details of each example are elaborated below:

1. Lava lamp

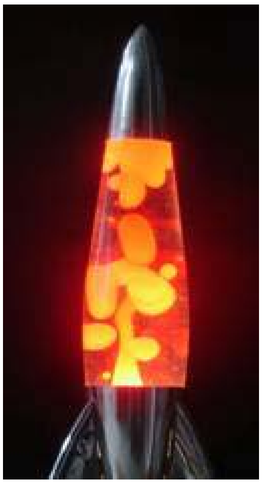

Figure 1: Lava lamp

As shown in Figure 1, why does the “lava” float and sink (Leif, 2008)?

While most students can easily invoke "thermal expansion" to explain the "floating" of the lava, they encounter serious difficulty in explaining the "sinking"[1].

The "lava" has slightly higher density at room temperature than the liquid, and a greater coefficient of thermal expansion. Thus, when heated by the lamp, the lava floats due to buoyant force.

In order to "sink" the lava, the containers need to taper towards the top, causing the temperature to drop[2].To derive the cooling rate (DT/t) depending on the radius (r) of the container, the heat transfer rate adopted is $\frac{Q}{t} = ms\frac{\Delta T}{t}$, where $\frac{Q}{t} \propto Area$,$\Rightarrow$ $\frac{\Delta T}{t} \propto \frac{Q/t}{m} \propto \frac{Area}{Vol} \propto \frac{2\pi r\Delta h}{\pi r^2 \Delta h} \propto \frac{1}{r}$, where Q is heat exhausted, T: temperature, t: time, m: mass, s: specific heat, and h is the height of the container. Thus, the narrower section has a faster cooling rate, causing the floating lava to sink. Therefore, this example illustrates that in addition to the concepts of buoyant force and thermal expansion, *thermal conduction* is required in order to explain the *sink* of the lava.

2. Hot-air balloon

Figure 2: Hot-air balloons

Why do hot-air balloons (Figure 2) float upwards? Which force lifts the system? While many students successfully respond: "buoyant force", many of them inappropriately attribute the buoyant force to "thermal expansion". They illustrate

[1] The narratives quoted in this paper are based on the author's teaching in introductory physics classes for engineering.

[2] Leif explained the narrowed top of the container causing the lava to sink verbally without sufficient argumentation.

thermal expansion as magnifying the oscillation of the chemical bonds for gas, implying the inadequate *static* model of ideal gas, rather than the *kinetic* model.

Instead of thermal expansion, the effective principle is the ideal-gas law (PV=nRT or PM=ρRT), where P is pressure, T: temperature, r: density, M: Molar molecular mass, and V: volume. Since a hot-air balloon is an open system, Pin=Pout, from PM=ρRT $\rho \propto 1/T$, then buoyant force $F_B = \Delta\rho_{(out-in)} \cdot V \cdot g$ can be applied. Thus, a hot-air balloon not only connects the ideal-gas law with Archimedes's buoyant force, but also confronts the *restriction* of "thermal expansion" in the gas system. In addition, the students' pitfall can be utilized to distinguish the *static* model for liquids and solids, and the *kinetic* model for gas, as well as to highlight the neglect of chemical bonds (nil potential energy) of ideal gas. Thus, the total internal energy of the gas system contains kinetic energy of molecules only.

3. Atomic explosion

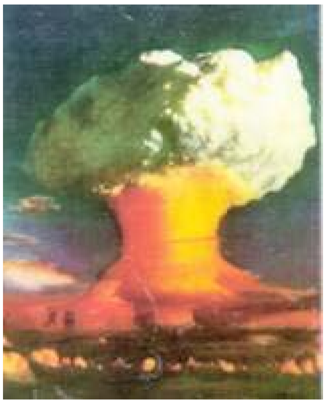

Fig. 3: Colors of atomic explosion

Figure 3 shows the color variation of the atomic explosion, which changes from yellowish at the bottom to white (clouds) at the top. While explaining the phenomenon, many students successfully respond that the white clouds are results of dramatic cooling. However, they tend to explain that based on PV=nRT, the explosion leads to a rise in temperature (V↗=> T↗). This justification is ineffective because they neglect the third variable (P), which is significantly reduced. The students' logic flaw found by the author is consistent with that found by Rozier and Viennot's (1991) study.

After challenging the ineffectiveness of the ideal-gas law, the 1st Law (Q+W=ΔU) is initiated, where Q is heat absorbed by the gas system, W: work done on the gas, and ΔU: change of the internal energy of the system. The explosion is fast enough to be treated as an adiabatic process; due to an adiabatic explosion (Q=0, W:-), the internal energy reduces (ΔU:-). By equating the internal energy (of the 1st law) to the kinetic energy (of kinetic theory), $\Delta U=\Delta E_k= \frac{5}{2}nR\Delta T$ for air, the reduction of the internal energy leads to a temperature drop, which becomes cold enough to condense the water vapor (the white cloud) at the top.

Since the notion of "internal energy difference (ΔU) due to work (W)" in Q+W=ΔU is less intuitive, the next example may reinforce the concept further.

4. Cold mountain-top and warm Foehn (chinook) winds

Why are mountain-tops cold and Foehn winds warm?

To explain this common meteorological phenomenon, the 1st Law (Q+W=ΔU) is more effective than the ideal-gas law (PV=nRT). When wind ascends from a mountain, the atmospheric pressure decreases, resulting in air expansion, which is fast enough to be treated as adiabatic (Q=0). Since work is done by the expanding air (W:—), the air loses internal energy (ΔU:—). Then, combining the 1st Law and the kinetic theory, the temperature drops ($\Delta U=\Delta E_k \propto \Delta T$), usually becoming cold enough to condense the damp air into rain

When the air blows from windward to leeward, dry wind descends and results in warm air, called Foehn (or Chinook). Foehn is adiabatic compression (Q=0, W:+ => ΔU:+ => ΔT:+). Therefore, Foehn is warm owing to the "work" done via air compression. Since Foehn is dryer than ascending wind, it has a greater temperature gradient compared with that of the ascending wind.

Examples 3 and 4 may help students to appreciate the function of the First Law in terms of distinguishing among heat (Q), work (W), and hotness (T). Warm Foehn is due to "work" (W) rather than "heat" (Q). In addition, hotness (ΔT>0) does not equate to "being heated" (Q>0), which students often have difficulty distinguishing (Erickson, 1979).

Conclusion

In sum, these four examples are aimed to illustrate the limitations/restrictions of popular theories and to highlight the functions/values of less intuitive concepts. For example, "thermal expansion" entails chemical bonds, which are limited to solids or liquids (#1), but inapplicable to ideal gas (#2). However, the state function of the ideal-gas law itself is insufficient to explain many real-life examples, e.g., adiabatic processes. Thereafter, the rather abstract principle of the 1st law is initiated and reviewed (#3 & #4).

The four examples are not novel, but were modified from the existing teaching resources (e.g., Walker, 1977) to enhance their pedagogical functions, including four features. 1. To improve visibility by assembling demonstrations (#1) or supplementing photos (#3) of existing conceptual questions. 2. To address students' prevalent pitfalls, e.g., highlighting the limitation of thermal expansion (#2) and the ideal-gas law (#3 & #4). 3. To bridge related principles, e.g., integrating the 1st law and kinetic theory ($\Delta U=\Delta E_k \propto \Delta T$, in #3 & #4). 4. To increase the sophistication of the scientific reasoning in order to improve students' intellectual satisfaction (Viennot, 2006), e.g., why the tapered shape at the top of the lamp allows the lava to sink (#1), and specifying the causality of "work alters temperature" ($W \rightarrow \Delta U \rightarrow \Delta T$) in adiabatic examples (#3 & #4).

The four examples were adopted in the author's introductory physics classes via various teaching activities. Example 1 was introduced along with a worksheet and Leif's article, becoming an open-form assignment. By means of a whole-class dialogue, Example 2 and Example 3 served as "appetizers" for initiating new topics, and Example 4 reviewed the First Law after the completion of teaching the topic.

By means of discussing these real-life examples, the "cold" physics theories can become sensible and relevant to daily life experiences. The functions, limitations, and relations of the physics theories are clarified and practiced repeatedly (Buncick, Betts and Horgan, 2001; Chang, 2011). Therefore, learning physics becomes more meaningful, sophisticated and heuristic.

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