Updating our language to help students learn: Mechanical energy is not conserved but all forces conserve energy

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GUEST EDITORIAL

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Conservation laws are some of the most fundamental principles in science. We recognize conserved quantities such as energy, momentum, and electric charge as much more rare and profound than quantities that are merely constant in some situations. The number of ice cubes in my freezer might be constant for a period of time. That doesn't mean ice cube number is a conserved quantity; their constant number is a consequence of particular circumstances for my freezer, not resulting from some profound natural principle. In fact, very few quantities are actually conserved, and all conservation laws that scientists have discovered are based on fundamental symmetries in nature.

In a national study of Content Knowledge for Teaching (CKT) energy, we found that a systems-based approach to energy conservation was among the most challenging areas of energy understanding for both high school physics teachers and physics majors.[1] These difficulties are rooted in the failure to distinguish a conserved quantity from a quantity that, like ice cubes, is merely constant for some systems in some situations. In this paper, we are building on these findings to argue that:

I. Mechanical energy, like any other sub-category of energy, is never a conserved quantity, even though it might remain constant for some systems during certain processes.
II. The language of "conservative" and "non-conservative" forces has no direct relationship to any conserved quantity and should be replaced with another labeling system, for example, "path-independent" and "path-dependent" forces (or some alternative taxonomy that better communicates the nature of the difference between these types of forces).

We recognize that these suggestions come with significant practical implications. Nearly all popular introductory physics textbooks introduce "non-conservative" forces. These textbooks agree that a force is non-conservative if the work done by that force is path dependent. With a couple of noteworthy exemptions,[2,3] these textbooks consistently describe mechanical energy as a quantity that is "conserved" as long as non-conservative forces do no work. There are significant differences in the way that the idea of conservation of mechanical energy is treated in various textbooks. We think one of the most coherent examples of a conditional conservation approach to mechanical energy is in Physics for Scientists and Engineers by Serway and Jewett where they write, "If nonconservative forces act in an isolated system, the total energy of the system is conserved, although the mechanical energy is not."[4] Jewett uses similar language in his articles on *Energy and the Confused Student*.[5] Some other treatments of mechanical energy and non-conservative forces are similarly coherent while others are significantly more problematic, in our view.

If mechanical energy is not a fundamentally conserved quantity based on a symmetry in nature, then why do most physics textbooks describe mechanical energy as a quantity that is sometimes *conserved*? Perhaps, this is because for many of the classic, idealized mechanics scenarios (frictionless inclines, ideal springs, perpetual pendula, and perfect projectiles), energy seemlessly converts between kinetic and gravitational or elastic while mechanical energy remains *constant*. These examples motivate an approach, in which mechanical energy is conditionally conserved in the absence of non-conservative forces. We object to this approach for practical and pedagogical reasons. Aside from gravitational, electrostatic, and magnetic interactions, essentially all macroscopic forces that students experience in their lives outside of physics class are at least somewhat path dependent. If we hope to empower students to apply their energy understanding to real-world situations that they care about, we should help them construct an energy model that applies to a world dominated by "non-conservative" forces.

Most physics teachers strive to help their students engage rigorously with the fundamental but challenging idea of energy conservation. Blocks slide to a stop and energy seems to vanish. Bubbles rise in a pool, and energy seems to come from nowhere. In these and every other aspect of our lived experience, total energy is always conserved.[6] In fact, conservation is perhaps the best explanation of what energy actually is. It's easy to recite the mantra that energy is never created or destroyed. Mapping out this idea in a physical world in which energy manifests in so many diverse and elusive ways is both formidable and extremely valuable. So why would we complicate one of the most powerful ideas in all of science by suggesting that mechanical energy is also a conserved quantity, but only sometimes? It is like first helping students recognize that mass is conserved during evaporation and then telling them that "liquid mass" is also a conserved quantity, but only sometimes, when "non-conservative" phase changes don't occur.

Instead, we could consistently emphasize the idea that energy is always conserved, for all systems and any force interactions, and mechanical energy, like all other subcategories of energy, is merely constant under specific circumstances for some systems. Distinguishing a conserved quantity from quantities that are merely constant is a crucial idea for understanding and applying conservation, yet it is also subtle. If we want students to deeply understand the fundamental idea that total energy of any system is always conserved (however, not necessarily constant) then we should not unnecessarily seed confusion by introducing some forces as "non-conservative." The very language of "non-conservative" forces suggests that these forces disrupt energy conservation. Who could fault a student for thinking that energy is not conserved when there is significant friction or air resistance? Who could fault a student for thinking that the energy conservation principle is unimpressive and irrelevant outside physics class if it doesn't apply to cases involving friction, air resistance, human beings, or useful mechanical devices? We hope our students will gain confidence in their understanding that energy is conserved even when "non-conservative" forces do work, so let's stop calling them non-conservative forces. In our view this approach is consistent with the "unified, contemporary approach to teaching energy" outlined in a recent article in this journal by Chabay, Sherwood and Titus.[7]

We realize that the language of "conservative" forces has a venerable legacy in our discipline. Changing this language would not merely entail changing introductory textbooks. We would need to change upper division mechanics textbooks. We contend, however, that this language is even confusing for many upper division students. For anecdotal evidence, try asking some upper division physics students why we call some forces non-conservative and how that relates to the principle of energy conservation. We hope that citizens who have completed only high school physics might have a relevant and flexible understanding of energy conservation. Therefore, it's essential that the physics majors who serve as their teachers harbor no confusions related to these ideas. The same should be expected of their teachers who do not have a physics or physics education major. There are additional challenges associated with the coherence of the energy instruction that this latter group receives in their preparation, which go beyond the scope of this article.

If we choose to move away from the language of "conservative" and "non-conservative" forces, we have several alternatives to choose from. We could call conservative forces *path-independent* or *configuration-forces* and non-conservative forces *path-dependent* or *motion dependent*. This new language would not automatically bring clarity and understanding, but it could prevent us from using language that is likely to confuse students unnecessarily. It might even help students engage with real-world stuff like dynamic climbing ropes and mountain bicycle shock absorbers for which forces depend both on configuration and motion. We hope this editorial will also serve as encouragement to physics education researchers to study the resources that students have for making sense of the complex relationship between forces and energy conversions. This research will help us to identify and prioritize language that supports student sense-making and inclusion over language that is familiar to those few of us who already feel included.[8]

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[1] L. Seeley, S. Vokos, and E. Etkina, "Examining physics teacher understanding of systems and the role it plays in supporting student energy reasoning," Am. J. Phys. **87**, 510–519 (2019).

[2] E. Etkina, G. Planinsic, and A. van Heuvelen, *College Physics: Explore and Apply* (Pearson, London, 2019).

[3] E. Mazur, *The Principles and Practice of Physics* (Pearson, London, 2015).

[4] R. Serway and J. Jewett, *Physics for Scientists and Engineers* (Cengage, Boston, MA, 2018), p. 186.

[5] John W. Jewett, Jr., "Energy and the confused student II: Systems," Phys. Teach. **46**, 81–86 (2008).

[6] We recognize that mass-energy is actually the fundamentally conserved quantity but for this editorial, we follow the approach of most introductions to energy conservation and ignore nuclear processes, in which mass is converted into other forms of energy. The approach we promote is epistemologically sound. One of the exciting chapters of the history of energy is the debate between physicists and geologists about the rate of cooling of Earth and the age of our planet, before radioactive decay in the Earth's interior was taken into account. Scientists introduce new forms of energy when conservation of total energy demands it.

[7] R. Chabay, B. Sherwood, and A. Titus, "A unified, contemporary approach to teaching energy in introductory physics," Am. J. Phys. **87**, 504–509 (2019).

[8] See the supplementary material at https://www.scitation.org/doi/suppl/10.1119/5.0067448 for further elaboration of an alternative scheme for classifying forces according to their role in energy transfers/conversions.