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On the origin of energy: Metaphors and manifestations as resources for conceptualizing and measuring the invisible, imponderable

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This article explores the origins of *metaphorical* language to describe energy by reviewing the historical development of the concept by physicists since the early 19th century. In addition to examples of historical and contemporary use of metaphors in academic writing, observable manifestations of energy are identified as the origin of energy "forms." The historical-philosophical review and presentation of examples from contemporary physics literature contribute a disciplinary foundation to recent claims about the productiveness of physics learners' use of metaphors and indicators to describe energy.
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I. ENERGY: CONCEPTUALIZING THE "IMPONDERABLE" WITH METAPHORS

> *"It is important to realize that in physics today, we have no knowledge of what energy is. […] It is an abstract thing in that it does not tell us the mechanism or the reasons for the various formulas" – Richard P. Feynman.*[1]

Energy in contemporary physics is an abstract, imponderable idea that has been proposed as a generalized conserved quantity. The law of conservation of this quantity is expressed as a mathematical principle that "says that there is a numerical quantity which does not change when something happens."[2] However, although energy was and is considered an imponderable concept, physicists (and scientists in other disciplines) were still able to develop a sophisticated understanding of it that goes beyond a mere mathematical description and formalism. In this paper, a brief review of the historical and philosophical roots of the energy concept in physics is presented, to argue that scientists were and are only able to investigate the multifaceted concept of energy by using models that employ *conceptual metaphors*.

Conceptual metaphors allow us to understand one idea in terms of another; they let us consider an imponderable idea in terms of a more experiential, "ponderable" idea. While related to *analogies*, metaphors differ in that they are not *explicitly* used as a tool to illustrate one phenomenon by comparing it to another one that shares its features. For example, an unobservable, microscopic property may be illustrated using a macroscopic analog (e.g., using egg crates to show properties of a semiconductor crystal[3]). Instead, metaphors *implicitly* ascribe properties of one idea to another. For example, the colloquial statement "spring break is coming up" ascribes a property of material objects—being able to move relative to an observer—to a temporal event. The use of this conceptual metaphor allows us to understand the abstract, imponderable phenomenon *time* in a similar way to how we understand the more directly experiential phenomenon *space*.

Different areas of physics use different models and metaphors for energy and therefore conceptualize energy in different ways. Quantum physics, for example, uses spatial metaphors for energy—electrons are said to be at different energy *levels*. In classical mechanics, container metaphors are more typical—a system is said to *contain* a certain amount of energy. No matter the particular sub-discipline, however, energy is commonly described using substance metaphors that are based on our experience with the material world. As such, conceptual metaphors enable the creation of rich narratives to explore phenomena involving energy.

Much has been written about the usefulness of conceptual metaphors for learning about and understanding energy in physics in the context of physics instruction.[4–9] However, little has been said about the origins of metaphorical language to describe the energetics of a system, or even the use of metaphors for describing energy in contemporary physics. In the past, researchers have primarily used analyses of textbooks—especially Feynman's writings—as the authority on what "energy" is to physicists.[5–7,10] Yet, a look at physicists' understanding of energy in the context of its historical development and an examination of metaphor use in recent physics literature was missing.

In this paper, the development of the modern energy concept is reviewed to show that the use of metaphors always has been and still is necessary for physicists to make sense of and communicate ideas about energy. The contemporary use of metaphors to describe energy dynamics is illustrated with an analysis of examples from the recent physics literature published in peer-reviewed journals. *Manifestations* of energy, which have been used as early as 200 years ago to classify energy into different *forms*, are shown to be useful for the quantification of energy.

A. The "indestructible, imponderable object" energy

The modern concept of energy was introduced into physics not as the result of empirical investigations alone, but through careful philosophical considerations. Physicists in the early 19th century attempted to find a unifying connection between the very much established theory of forces and motion, and the still rather new theory of heat. While many agreed that heat was a form of motion,[11] and that it was created by mechanical and chemical processes, the quantitative nature of the relationship between heat and motion was not known.[12] Scientists also knew that objects in motion had a property they called *vis viva*—the "living force." After a century-long debate, physicists agreed[13] that the quantity of this property was mv^2. Although generally assumed to be a conserved quantity, empirical results implied that this property of moving objects was not *universally* conserved.

At the time, the word "force" was ambiguously used for both the Newtonian force concept and the developing energy concept. Thomas Young proposed a new name for *vis viva*: *Energy*.[14] However, Young's nomenclature did not catch on for decades; his contemporaries still used the word force in the ambiguous way that must be interpreted appropriately according to the context in which it appears.

At least 12 scientists were simultaneously working on the problem of energy conservation in the first half of the 19th century.[15] According to Kuhn, some of them (Carnot, Séguin, Holtzmann, Hirn) were convinced that heat and mechanical work could be transformed into each other. Others (Mohr, Grove, Faraday, Liebig) had already argued that the world could be described in terms of a unified force, which is manifested in various forms. In the 1840s, rigorous experiments on the equivalence between these various forms were conducted, and formal derivations of a general law of energy conservation were proposed by Joule, Colding, Mayer, and Helmholtz. Joule and Colding, both inspired by religious beliefs, independently postulated the "conservation of forces" as a way to maintain god-given order in the universe[16] and performed experiments to investigate quantitative relationships between different kinds of forces (heat, motion, etc.). A year before Joule published his results, Julius Robert Mayer formally derived a general law of energy conservation. While Mayer's law was based on a slightly flawed argument,[17] it presents an important milestone in the development of the modern energy conservation principle.

In his paper "Bemerkungen über die Kräfte der unbelebten Natur"[18]—"Remarks on the forces of the inanimate nature"[19]—Mayer attempted to clarify the developing energy concept, which he referred to as something "unknown, unsearchable, hypothetical."[20] Using the scholastic principle "causa aequat effectum"—"cause equals effect"—he derived the conservation of energy in a logical, philosophical argument. He argued that a cause and any of its effects are merely different forms of appearance of one and the same "object" and that "causes are (quantitatively) *indestructible* and (qualitatively) *changeable* objects."[21] According to Mayer, there have been only two kinds of causes identified in nature: matter, which has the "property of ponderability and impenetrability,"[22] and forces (in the sense of energy), which do not have those properties but are instead "indestructible, changeable, imponderable objects."[23] Mayer discusses several examples of forces that can be changed (or transformed) into each other. These are what we would call "energy forms" today. For example, he describes the equivalence of potential energy ("Fallkraft" or "fall force," which he calls the energy associated with spatial distance between ponderable, or material, objects[24]) as a cause, and kinetic energy ("Fall," the fall, or more general "Bewegung," "motion") as its effect. These are only two of the manifestations Mayer presents of the same indestructible and imponderable object, energy.

A few years later, Hermann von Helmholtz derived a version of the modern energy conservation law in his treatise "über die Erhaltung der Kraft"—"On the conservation of force."[25] Helmholtz started with the two assumptions that (1) perpetual motion is impossible and (2) all "effects in nature" are caused by central Newtonian forces,[26] to develop the argument that the quantitative properties of forces (i.e., energy) were conserved, despite their qualitatively different manifestations.[27,28] The nature of the conserved "object," however, eluded Helmholtz, just as it did Mayer. The closest Helmholtz came to a general definition of the transcendent energy was giving it the name "Arbeitskraft," literally "work force" or, more adequate to its meaning, "labor power"—the power or ability to perform (mechanical) work.[29]

Even half a century later, physicists were still struggling to define what energy is. Poincaré, for example, wrote in the preface to the first edition of his 1892 textbook on thermodynamics:[30] "In every special instance, it is clear what energy is and we can give at least a provisional definition of it; it is impossible, however, to give a general definition of it. If one wants to express the law [of energy conservation] in full generality, one sees it dissolve before one's eyes, so to speak leaving only the words: *There is something that remains constant*."[31]

B. Models as allegories: Using metaphors to understand energy

According to Clarke,[32] "Modern physics gained conceptual and technological purchase on the imponderable forms and phenomena of heat, light, gravity, and electromagnetism not by seizing reality bare-handed but, to a significant extent, through scientific allegories:"[33] Physicists constructed and refined narratives about reality ("factual fiction") as increasingly sophisticated models for energy. In fact, even the name energy was not arbitrarily proposed by Young but rather because of its connotations in literary use. *Energy*, according to the Oxford English Dictionary, originally made its way into the English language in the 16th century (in an interpretation of Aristotle's use of ἐνέργεια) referring to "force or vigour of expression" in speech or writing.[34] At the beginning of the 19th century, the word was also used to mean "Vigour or intensity of action […] The capacity and habit of strenuous exertion," which explains Young's proposal to rename the "living or ascending force:" He thought the new term would "[indicate] the tendency of a body to ascend or to penetrate to a certain distance."[35]

The allegorical character of current energy models becomes apparent, for example, in two particular models that have been proposed in the science education literature and that were previously summarized by the author as follows:[36]

> *(1) In [a Forms model[10]], energy is described as something that objects with* observable and changeable properties *can have. It has different* forms*, each of which is associated with one of those properties. When two properties of the same object* change *simultaneously, energy is being* transformed *from one form to another. When one and the same property* changes *simultaneously for two different objects, it is reasonable to say that energy was* transferred *from one object to the other.*

This model is represented in the AAAS Benchmarks for Scientific Literacy[37] and at the core of the "Crosscutting Concept Energy" in the Next Generation Science Standards for K-12 science education.[38] Therefore, it is likely the model of—and the corresponding language to describe—energy most students are familiar with when they enter our university physics classes.

> *(2) A different model of energy, a Stores and Transfer model, places emphasis on processes of*

> *transfer and transformation.*[39] *The focus in this model is on* storage and transfer *of energy in a system. The model postulates that energy can only be stored in three stores within a system. These means of storage are associated with motion, position, and intrinsic properties like temperature and phase (for more detail see [Jewett's] original publication). If there is an internal transfer of energy within a system* and *from one store to another, an energy transformation has occurred. The three primary mechanisms of energy transformations are work, and chemical and nuclear reactions. Energy transfers across system boundaries may occur by mechanisms that can be categorized into six processes: work, heat, matter transfer, mechanical waves, electromagnetic radiation, and electrical transmission.*[40]

Both models allow a physicist (or a learner of physics) to formulate distinct narratives of physical phenomena involving energy and explore these phenomena within the narrative.

Fundamentally at the heart of a narrative about energy (using either one of the two presented models or an entirely different one) is the use of conceptual metaphors. In particular, the use of *substance metaphors* has permeated the history of the developing energy concept. Planck, for example, pointed out that drawing analogical parallels between energy and matter was helpful in establishing acceptance of the energy concept among scientists of the 19th century.[41] He also strongly suggested that a substance-like conception of energy, in addition to adding clarity to the abstract concept, would inspire progress in the development of energy theory that goes beyond mere quantitative considerations. Such a theory of energy, Planck argued, would allow scientists to not only know the number that represents a quantity of energy but also enable them to identify the existence of energy within a system and trace it across system boundaries.[42]

Even Feynman,[1] who has been cited on numerous occasions[43] for his definition of the energy concept as a purely abstract and mathematical principle,[44] used a variety of conceptual metaphors for energy throughout his lectures in his illustrations of how energy behaves and has consequences for physical systems. Many of the metaphors he used indicate the treatment of energy as a substance-like quantity.[5]

II. ENERGY IS A SUBSTANCE-LIKE ENTITY: EXAMPLES FROM PHYSICS RESEARCH

The use of a substance metaphor for describing energy has been identified as a useful resource commonly activated by students in educational settings.[4–9] It has been argued that the use of multiple ontological metaphors is productive for experts and students alike. According to Lakoff and Johnson,[45] "Understanding our experiences in terms of objects and substances allows us to […] refer to them, categorize them, group them, and quantify them—and, by this means, reason about them."[46] In this view, conceptualizing energy as a substance or entity enables us to treat it as a physical quantity that we can study.

Lakoff and Johnson further argue that ontological metaphors can be elaborated, using so-called structural metaphors[47] to describe a phenomenon in more detail. For example, the abstract concept "mind," seen as an entity—a bounded object—can be further described as a machine or as a brittle object.[48] In the former example, "The mind is a machine" then is the metaphor that provides structure to the concept of mind using the well-structured (and more readily understood) concept "machine." This metaphor can be found, for example, in statements like "We're still trying to *grind out* the solution to this equation."[49]

In this section, examples of how physicists use metaphors for energy in their scientific writings are presented. In particular, the structural metaphors that elaborate and help us make sense of the scientists' understanding of energy are highlighted.

A. Energy is *deposited*

Belying the assertion that energy is merely an abstract, numerical quantity, physicists commonly treat energy as if it was a substance or an object that, for example, can be *deposited*. A Google Scholar search for scientific articles published since 2011 in physics journals that contain the phrase "deposited energy" yields about 1800 results.[50] A closer look at the journal names and abstracts of these papers reveals that this phrase is mostly used in areas of applied physics, medical physics, and condensed matter physics, especially in the context of irradiating materials using light (e.g., laser, X-rays) or particle beams (e.g., electrons, ions). In this section, a paper by Mintoussov *et al*.[51] published in the *Journal of Physics D: Applied Physics*, one of the more frequently cited[52] papers in this list, will be used as a representative case to illustrate how physicists productively use structural metaphors that elaborate a substance-like treatment of energy to convey their findings. The use of these metaphors furthers our understanding of energy in the particular context presented in the paper and allows the authors to go beyond the mere reporting of energy amounts in the form of numbers.

In their article, Mintoussov *et al*. describe "Fast gas heating in nitrogen-oxygen discharge plasma," and specifically, the "Energy exchange in the afterglow of a volume nanosecond discharge at moderate pressures." The authors built a discharge tube that allowed them to release a high-voltage pulse into synthetic air (80% N_2, 20% O_2) or highly pure nitrogen. A number of measurement and detection mechanisms allowed them to deduce the "current and energy delivered to the discharge" and measure the "dynamics of the potential drop along the discharge tube starting from the cathode towards the anode."[53]

The article title and the description of the experimental procedure make use of a substance metaphor for energy: The phrase "energy exchange" in the title suggests an ontological view of energy as having real existence, as something that can be taken and given (or, with Planck above, traced across system boundaries). The description of energy as something that can be "delivered" further illustrates this view. Throughout their paper, the authors use the phrase "deposited energy" to refer to energy that was transferred to the gas by the electric discharge. In addition, the authors describe how the deposited energy is "*distributed* between electronic and vibrational states of particles"[54] (emphasis added here and in subsequent quotes), using a metaphor of spatial spreading to localize the energy. These metaphors suggest that energy has certain qualities of a substance or entity: Energy can not only be transferred across system boundaries but also localized within a system.

B. Energy is a *cause*

Treating energy as a bounded object by using entity metaphors, the authors also ascribe agency to it: "energy *goes* to fast gas heating" (abstract), it "*goes* to excitation of electronic degrees of freedom,"[55] "vibrational excitation of molecular nitrogen," and "rotational excitation of molecules and directly to gas heating"[54] are just a few examples of how the authors ascribe the ability of energy to act and cause things to happen. These statements directly use the structural metaphor "Energy is an agent." While the use of this metaphor here does not directly describe an action on another object, it is implied that energy in each case enables a particular phenomenon: the excitation of molecules and, as a consequence, gas heating. A metaphor that describes energy as an entity that enables processes was identified by Scherr *et al*. as a "stimulus metaphor."[7] Scherr *et al*. wrote about the usefulness of a stimulus metaphor in learning about energy: "The stimulus metaphor is a conceptualization that supports features valued in sociopolitical discourse, specifically the necessity of energy for sustaining activity. It also supports the idea that energy is the 'ability to do work,' and to some extent the causal mechanistic relationship between energy and forces."[56]

The stimulus metaphor is remarkable in its similarity to the predominant conceptualization of force at the beginning of the 19th century. As history shows, thinking of energy as a cause that has an effect can be a productive starting point for the development of an understanding of energy conservation. Several curricula have been developed that use a conceptualization of energy as a cause of changes.[57]

C. Energy is *fuel*

The work of Mintoussov *et al*. states that "energy goes to" vibrational and rotational excitation and heating which suggests that the entity energy is a requirement for motion and heating. The notion of energy as a requirement for action and the authors' conclusion that "excitation energy is *spent* for gas heating,"[58] as well as the notion of an *energy cost* associated with "atomic oxygen production"[59] are compatible with the structural metaphor "Energy is a resource."[60] According to Lakoff and Johnson, "A material resource is a *kind* of substance, can be *quantified* fairly precisely, can be assigned a *value* per unit quantity, serves a *purposeful* end, [and] is *used up* progressively as it serves its purpose"[60] (emphases in the original). The metaphor "Energy is fuel" provides similar structure and makes use of our everyday experience with *actual* substances that can transfer and provide energy (for example, to power an engine):

> *Fuel […] is a (literal) material substance that contains energy and (taken together with oxygen) can transfer that energy to other objects at a selected time. In physics, any object can possess and transfer energy. Fuel is distinctive in that the energy of interest is often chemical energy; the transfer often takes place by combustion; and the desired effect of the energy transfer is to result in mechanical work, so that the energy of interest is the "useful" energy and the objects of interest are those we use as "power sources" (wind, gasoline, batteries, food).*[61]

Conceptualizing energy as a resource or fuel is of particular value in physics because it brings with it certain productive connotations. Energy in this view is seen as measurable and therefore quantifiable, and it can be assigned numerical *and* qualitative value, for example *usefulness*, which is related to *energy degradation* and the availability of energy for mechanical energy transfer.[62,63]

D. Other examples

Many more examples can be found of physicists using various metaphors for energy in their scholarly writing. In a paper about laser-welding of polyethylene, for example, Visco *et al*.[64] made use of a substance metaphor by describing the *absorption* and *deposition* of energy. In addition, they also ascribe agency to the energy with a stimulus metaphor when they narrate that "the laser pulse energy *pushes* out the carbon nanotubes from the polymeric sheet surface" and that the "adsorbed [sic] laser energy *produces* a spot morphology."[65] Susskind[66] used several energy metaphors in a paper about some implications of certain principles in string theory to describe the process of hadronization. He describes the "energy to create the string" (stimulus metaphor), then locates the energy in the string and a quark (container metaphor), and eventually states that in the process, energy gets "used up" (fuel metaphor).[67]

The use of multiple metaphors is a disciplinary productive resource for thinking about and communicating ideas about energy. Energy is a phenomenon so complex that multiple, coherent but not necessarily consistent, metaphors are necessary to characterize and describe it.[6] A conceptualization of energy as an entity allows physicists to classify energy into different forms and see it as quantifiable.

III. FORMS OF ENERGY: MAKING ENERGY PONDERABLE

The historical-philosophical review of the energy concept in physics above allows for a brief review of how the notion of *energy forms* helps physicists in their investigation of phenomena involving energy. After a short historical motivation, this is illustrated in this section with more examples from recent physics research.

A. The study of energy as the study of its forms

A hallmark of common conceptualizations of energy in physics is the idea of *metamorphosis*. Clarke wrote that "energy assumed its modern scientific meaning in order to encompass the broad phenomenology of physical forms unified by the principle of the conservation of energy, also known as the first law of thermodynamics. Numerous energies are constantly being converted from one form to another, altering quality without loss of absolute quantity."[68] Energy is a conserved quantity that cannot be directly perceived. We can only describe energy's effects on our senses or measurement instruments and infer about its existence and involvement in physical phenomena through the ways in which it manifests itself. These measurable manifestations of energy are its "essential determinant principles," or "forms."[69] Assigning form—a quality literally reserved for material substances—to energy is in itself a metaphorical act that attributes substance-like properties to energy. An important implication of this metaphor is the understanding that while the form, or appearance, of a substance (or substance-like quantity like energy) can change, the substance itself (energy) remains unaltered.

The concept of energy was developed as a consequence of experimental observations, as well as scientists' determination to find conserved quantities and to reduce their observations and findings to general principles. From the early days of energy theories, physicists have sought to identify the various manifestations of energy. While Mayer identified individual forms like motion, "gravity," "heat," "electricity," etc., Helmholtz categorized the phenomena associated with Mayer's forms into the two main energy forms "lebendige Kraft" ("living force," which we call kinetic energy today) and "Spannkraft" ("tension," or potential energy).[14] This distinction into two basic forms of energy is still accepted in physics today: one that is manifest in an object's motion and another one which depends on the configuration of the constituents of a system and can manifest itself in various ways.[70]

The investigation of energy in physical systems is, to this day, an inquiry into its forms. According to Maxwell, "in the study of any new phenomenon our first inquiry must be, How can this phenomenon be explained as a transformation of energy? What is the original form of the energy? What is its final form? and What are the conditions of the transformation?"[71]

B. Observing manifestations as evidence for the existence of energy and as means to quantify energy

Mintoussov *et al*. pointed out that energy in their study was "deduced,"[53] and they provide detailed information about which manifestations were measured and how energy quantities were calculated from these measurements. For example, the "input energy" delivered to the 22-kV discharge was determined by examining the incident, reflected, and transmitted pulses by measuring the electric current through the coaxial cables delivering the 30-ns pulses to the discharge tube. However, in this particular measurement, the researchers had to infer the momentary current from voltage measurements across shunts in the coaxial cables before and after the discharge tube, using

$$dI_{\text{discharge}} = \frac{dV_{\text{shunt}}}{R_{\text{shunt}}} \,. \tag{1}$$

This current flow in the coaxial cables is induced by the 22-kV ($= V_{\text{pulse}}$) discharge in the gas between the two electrodes within the discharge tube. One directly measurable energy manifestation in this case is therefore the voltage drop across the shunt resistors which results from this current. The amount of energy deposited into the tube by the discharge can then be calculated with the equation,

$$E_{\text{input}} = V_{\text{pulse}} \int \frac{V_{\text{shunt}}(t)}{R_{\text{shunt}}}\, dt \,. \tag{2}$$

While the authors inferred the quantity of the "input" or "deposited energy" of the discharge from the electric current through shunts in the coaxial cables delivering the energy from a high voltage pulse generator, the discharge itself is an observable manifestation of this energy. Therefore, the authors also call this energy form "discharge energy." It is the stated goal of Mintoussov *et al*. to find the fraction of discharge energy that contributes to the process of "gas heating," which results in an increased gas temperature as a manifestation of the discharge energy portion that is absorbed by the gas.

The authors determined the gas temperature—a measure for the average kinetic energy of the molecules comprising the gas—by measuring the rotational emission spectrum of the gas during the discharge and comparing this measurement to simulated spectra for various temperatures. This rotational spectrum, however, is itself a result of photons emitted by gas molecules returning to a lower energetic state after having absorbed a certain amount of the discharge energy deposited into the gas and therefore a manifestation of this absorbed energy that the authors call "excitation energy." Additional forms of energy that the authors mention in their paper are "vibrational energy," referring to the energy absorbed into a vibrational state of a molecule and "kinetic energy," which seems to primarily refer to translational kinetic energy of dissociation products like oxygen atoms.

The inquiry into the various manifestations of energy is a powerful way of analyzing systems according to the fundamental law of energy conservation. On rare occasions, physicists propose revolutionary new *fundamental* forms of energy when the principle of energy conservation seems violated while using only the currently agreed upon energy forms. For example, Einstein proposed the existence of *rest energy* in his development of the theory of special relativity. This energy form is inherent to systems for which a frame of reference exists in which the momentum of the system vanishes. It only depends on the total mass of a system, $E = mc^2$; in this case, energy is manifested in the mass (or inertia) of an object.[72]

"Inventing" non-canonical energy forms (be it context-specific sub-types of conventional energy types like excitation energy as a form of kinetic energy, or fundamentally new energy forms like Einstein's rest energy) is routine and useful for physicists because it allows for the distinction between the different manifestations of energy and between different mechanisms of energy transfer in particular contexts. With the terminology of energy forms and the implicit treatment (via conceptual metaphors) of energy as having substance-like properties, a narrative description of energy states and dynamics in a system of interest becomes possible. As such, we can expand our understanding of energy and its role in physical processes beyond a purely mathematical treatment.

IV. CONCLUSION

In this paper, our contemporary understanding of energy as an abstract concept that cannot be observed or measured directly was characterized. To still be able to reason about the energetics of a system of interest, physicists routinely and implicitly use *metaphors* for energy, and they identify *manifestations* of energy or *indicators* for energy involvement.

In the past, students' use of certain metaphors, especially the substance metaphor, has been taken as an indication for their flawed, unscientific understanding of energy.[73] More recently, however, researchers have suggested that students' use of metaphors to describe energy can be seen as a productive resource for making progress toward the systematic investigation and description of the energy dynamics in systems of interest.[8,74] Recognizing disciplinary progenitors in students' ideas and fostering them in classroom discourse is important to help students develop scientific understandings of energy. This review shows the abundance and importance of metaphors to describe energy and of energy forms as the perceivable, measurable manifestations of energy in physics. It is the author's hope that the presented examples will help instructors see the disciplinary value in their students' ideas about energy.

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[20]"…knüpft sich an die Benennung Kraft vorzugsweise der Begriff des unbekannten, unerforschlichen, hypothetischen," Reference 18, p. 3.
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[22]"Eigenschaft der Ponderabilität und Impenetrabilität." Reference 18, p. 4.
[23]"Kräfte sind also: unzerstörliche, wandelbare, imponderable Objecte." Reference 18, p. 4.
[24]Reference 18, p. 5.
[25]H. Helmholtz, *Über die Erhaltung der Kraft, Ostwald's Klassiker der exacten Wissenschaften* (Verlag von Wilhelm Engelmann, Leipzig, Germany, 1889).
[26]"Die Herleitung der aufgestellten Sätze kann von zwei Ausgangspunkten angegriffen werden, entweder von dem Satze, dass es nicht möglich sein könne, durch die Wirkungen irgend einer Combination von Naturkörpern auf einander in das Unbegrenzte Arbeitskraft zu gewinnen, oder von der Annahme, dass alle Wirkungen in der Natur zurückzuführen seien auf anziehende und abstossende Kräfte, deren Intensität nur von der Entfernung der auf einander wirkenden Punkte abhängt." Reference 25, p. 3.
[27]For example, the spatial separation of objects can result in motion of one or both objects.
[28]F. Bevilacqua, "Helmholtz's Ueber die Erhaltung der Kraft: The emergence of a theoretical physicist," in *Hermann von Helmholtz and the Foundations of Nineteenth-Century Science*, edited by D. Cahan (University of California Press, Berkeley, CA, 1993), Chap. 7, pp. 291–333.
[29]A. Rabinbach, *The Human Motor: Energy, Fatigue, and the Origins of Modernity* (University of California Press, Berkeley, CA, 1992), p. 55.
[30]H. Poincaré, *Cours de Physique Mathématique. Thermodynamique*, 2nd ed. (Gauthier-Villars, Imprimeur-Libraire, Paris, France, 1908).
[31]"Dans chaque cas particulier on voit bien ce que c'est que l'energie; l'on en peut donner une définition au moins provisoire; mais il est impossible d'en trouver une définition générale. Si l'on veut énoncer le principe dans toute sa généralité et en l'appliquant à l'Univers, on le voit pour ainsi dire s'évanouir et il ne reste plus que ceci: *Il y a quelque chose qui demeure* constant." Reference 30, p. IX. Translation adapted from R. Feistel and W. Ebeling, *Physics of Self-Organization and Evolution* (Wiley-VCH, Weinheim, Germany, 2011), p. 55.
[32]B. Clarke, *Energy Forms: Allegory and Science in the Era of Classical Thermodynamics* (University of Michigan Press, Ann Arbor, MI, 2001).
[33]The Oxford English Dictionary, <www.oed.com>, defines allegory as "a story, picture, etc., which uses symbols to convey a hidden or ulterior meaning" or as "an extended or continued metaphor."
[34]*energy*, *n*. Oxford English Dictionary Online, <http://www.oed.com/view/Entry/62088>.
[35]T. Young, *A Course of Lectures on Natural Philosophy and the Mechanical Arts* (Joseph Johnson, St. Paul's Church Yard, London, England, 1807), Vol. I, p. 44.
[36]B. W. Harrer, V. J. Flood, and M. C. Wittmann, "Students talk about energy in project-based inquiry science," AIP Conf. Proc. **1513**, 162–165 (2013).
[37]AAAS Benchmarks for Scientific Literacy Online, <http://www.project2061.org/publications/bsl/online/index.php?chapter=4>.
[38]NGSS Lead States, *Next Generation Science Standards: For States, by States* (National Academies Press, Washington, DC, 2013).
[39]J. W. Jewett, "Energy and the confused student IV: A global approach to energy," Phys. Teach. **46**, 210–217 (2008).
[40]A conceptualization of energy with the latter model is facilitated, for example, in the representations *Energy Theater*: A. R. Daane, L. Wells, and R. E. Scherr, "Energy theater," Phys. Teach. **52**, 291–294 (2014); and *Energy Tracking Diagrams*: R. E. Scherr, B. W. Harrer, H. G. Close, A. R. Daane, L. S. DeWater, A. D. Robertson, L. Seeley, and S. Vokos, "Energy tracking diagrams," Phys. Teach. **54**, 96–102 (2016).
[41]"Ohne Zweifel beruht zum großen Teil auf dieser Analogie die verhältnismäßig überraschende Leichtigkeit und die sieghafte Klarheit, mit der sich das Prinzip der Erhaltung der Energie binnen weniger Jahre die allgemeine Anerkennung eroberte und in der Überzeugung eines jeden festsetzte." Reference 14, p. 116.
[42]"Indessen ist doch gerade an dem genannten Beispiel, dem später noch andere folgen werden, unverkennbar, daß mit der hier in Rede stehenden substanziellen Deutung des Begriffes der Energie nicht nur eine Vermehrung der Anschaulichkeit, sondern auch ein direkter Fortschritt in der Erkenntnis verbunden ist. Dieser Fortschritt beruht auf der Anregung zur weiteren physikalischen Forschung. Man wird sich nun nicht mehr damit begnügen, den Zahlenwert der Energie des Systems zu kennen, sondern man wird versuchen, die Existenz der verschiedenen Arten der Energie an den verschiedenen Elementen des Systems im einzelnen nachzuweisen, und den Übergang in andere Formen und zu anderen Elementen

ebenso verfolgen, wie die Bewegung eines Quantums Materie im Raum." Reference 14, pp. 117–118.

[43]For example, A. B. Arons, "Development of energy concepts in introductory physics courses," Am. J. Phys. **67**, 1063–1067 (1999); A. Brook and R. Driver, *Aspects of Secondary Students' Understanding of Energy: Full Report* (University of Leeds, Centre for Studies in Science and Mathematics Education, Leeds, UK, 1984); R. Trumper, A. Raviolo, and A. M. Shnersch, "A cross-cultural survey of conceptions of energy among elementary school teachers in training—empirical results from Israel and Argentina," Teach. Teach. Educ. **16**, 697–714 (2000); D. M. Watts and J. K. Gilbert, "Enigmas in school science: Students' conceptions for scientifically associated words," Res. Sci. Technol. Educ. **1**, 161–171 (1983).

[44]"There is a fact, or if you wish, a *law*, governing all natural phenomena that are known to date. There is no known exception to this law—it is exact so far as we know. The law is called the *conservation of energy*. It states that there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens." Reference 1, p. 4-1.

[45]G. Lakoff and M. Johnson, *Metaphors We Live By* (The University of Chicago Press, Chicago, IL, 2003).

[46]Reference 45, p. 25.

[47]Reference 45, p. 61.

[48]Reference 45, pp. 27–28.

[49]Reference 45, p. 27.

[50]Search conducted on February 24, 2016, using <http://scholar.google.com>.

[51]E. I. Mintoussov, S. J. Pendleton, F. G. Gerbault, N. A. Popov, and S. M. Starikovskaia, "Fast gas heating in nitrogen-oxygen discharge plasma: II. Energy exchange in the afterglow of a volume nanosecond discharge at moderate pressures," J. Phys. D: Appl. Phys. **44**, 285202 (2011).

[52]43 citations; most papers in this list were cited on the order of 10 times.

[53]Reference 51, p. 3.

[54]Reference 51, p. 7.

[55]Reference 51, p. 1.

[56]Reference 7, p. 4.

[57]For example, J. Nordine, J. Krajcik, and D. Fortus, "Transforming energy instruction in middle school to support integrated understanding and future learning," Sci. Educ. **95**, 670–699 (2011); N. Papadouris, C. Constantinou, and T. Kyratsi, "Students' use of the energy model to account for changes in physical systems," J. Res. Sci. Teach. **45**, 444–469 (2008).

[58]Reference 51, p. 8.

[59]Reference 51, p. 11.

[60]Reference 45, p. 65.

[61]Reference 7, p. 3.

[62]cf., A. R. Daane, S. Vokos, and R. E. Scherr, "Learner understanding of energy degradation," in *Proceedings of the Physics Education Research Conference*, Portland, OR, 2013, edited by P. V. Engelhardt, A. D. Churukian, and D. L. Jones, pp. 109–112.

[63]Often-heard associated statements like, "energy is lost to heat," are themselves metaphorical, indicating a substance-like energy that is not recoverable (or find-able) for use in mechanical energy transfer.

[64]A. M. Visco, N. Campo, L. Torrisi, and F. Caridi, "Effect of carbon nanotube amount on polyethylene welding process induced by laser source," Appl. Phys. A **103**, 439–445 (2011).

[65]Reference 64, p. 442.

[66]L. Susskind, "String theory," Found. Phys. **43**, 174–181 (2013).

[67]All quotes appear in Ref. 66 on p. 175.

[68]Reference 32, p. 20.

[69]*form*, *n*. [Def. 4.a]. Oxford English Dictionary Online, <http://www.oed.com/view/Entry/73421>.

[70]Reference 12, pp. 330–332.

[71]J. C. Maxwell, "Hermann Ludwig Ferdinad Helmholtz," Nature **15**, 389–391 (1877). Quote appears on p. 390.

[72]A. Einstein, "Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?," Ann. Phys. **323**, 639–641 (1905).

[73]For example, D. M. Watts, "Some alternative views of energy," Phys. Educ. **18**, 213–217 (1983); and J. Solomon, "Messy, contradictory and obstinately persistent: A study of children's out-of-school ideas about energy," Sch. Sci. Rev. **65**, 225–229 (1983).

[74]H. C. Sabo, L. M. Goodhew, and A. D. Robertson, "University student conceptual resources for understanding energy," Phys. Rev. Spec. Top.—Phys. Educ. Res. **12**, 010126 (2016).

[75]B. W. Harrer, "Identifying productive resources in secondary school students' discourse about energy," Doctoral dissertation, University of Maine, Orono, ME, 2013.