Compartmentalization of energy concepts—definitions, ontologies, and word associations

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The language used to describe concepts related to energy within the disciplines of physics and chemistry was interpreted in terms of the common definitions and ontologies of energy. Experts and novices in both domains were asked to define energy, kinetic energy, and potential energy and perform word association tasks as part of a larger semi-structured interview on energy. The provided responses were coded and analyzed based on definition and ontology to determine consistency. In general, a range of views on energy was seen, with most novices defining energy as “the ability to do work.” Experts tended to describe energy more generally based on its characteristics. These are preliminary results related to a larger study looking at the compartmentalization of energy concepts between the domains of chemistry and physics.

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I. INTRODUCTION

Energy is a universal concept present in many sub-disciplines of science, ranging from physics to chemistry to biology, but is often first introduced in introductory physics and chemistry courses. Depending upon the context, some characteristics of energy are emphasized, while others are obscured [1]. This may lead to the compartmentalization of ideas based on context, even though the concept of energy itself is context-independent [2,3]. Therefore, it is important to better understand the effect chemistry- and physics-related surface features, which provide context for a situation, have on how people think and talk about energy.

There are three common definitions of energy, each with its own advantages and disadvantages: the ability to do work, a causal agent, and a measure of physical change in a system [4]. The first definition refers to the transfer of energy. Although it is the most common definition, especially amongst physicists, “the ability to do work” is not very intuitive and must be defined in conjunction with the concept of work, which has limited utility in chemical contexts. Energy as a causal agent implies that energy is something that causes motion. This view is considered a misconception, as it conflates the ideas of energy and force, but is persistent both in everyday language and in instruction. The last definition, though viewed as the most applicable, does not really define energy more than it describes it.

Energy can also be understood in terms of its ontology, which is the classification of its meaning based on its usage and context. There are three main ontologies of energy: energy as a substance, energy as a stimulus or causal agent, and energy as a vertical location [5]. An object *having* a certain amount of energy is an example of the substance ontology; energy is a substance that an object can possess. Energy can also be described as *causing an effect* on objects, which would imply the

stimulus ontology. Like the causal agent definition of energy, this ontology combines the ideas of energy and force and is usually avoided by experts. Finally, the energy of an object is often discussed as moving *from* one value *to* another value. Here energy is thought of as vertical locations with one “higher” than another. This is commonly seen in chemistry in terms of the energy levels of an electron in an atom.

By interpreting the language used to describe energy, we hope to better understand the effect of context on the definitions and ontologies used by novices and experts. This paper presents preliminary results related to the definitions, words, and ontologies used by interviewees when asked about energy, kinetic energy, and potential energy.

II. METHODOLOGY

A total of 20 volunteers ranging from first-year undergraduates through professors were recruited from chemistry and physics courses at both the introductory and advanced levels. All 18 of the undergraduate and graduate student volunteers were majoring in either chemistry or the life sciences. The experts were professors in the chemistry and physics departments. All volunteers for this study had previous experience with chemistry at both the high-school and university levels. Ninety percent of volunteers had previous exposure to introductory physics at the high-school level, but only 45% of volunteers had experience at both the high-school and university levels.

All volunteers were asked the same set of questions in individual semi-structured interviews. Audio recordings were collected in order to obtain an accurate transcript of each interview. The first set of questions had subjects define the terms “energy”, “kinetic energy”, and “potential energy” in their own words. Next, they were asked for words they associate with “energy”, “kinetic energy”, and “potential energy”. The remaining questions

revolved around prompts given to the subjects to probe the compartmentalization of energy concepts between the domains of chemistry and physics. This paper focuses on the definition and word association data.

III. RESULTS AND DISCUSSION

After transcription, each response was coded according to which of the above definitions of energy and which ontologies were invoked for energy, kinetic energy, and potential energy in the definitions and word associations. Responses could be classified as containing references to more than one definition or ontology. Answers to the word association tasks were grouped according to common themes found throughout all of the responses.

A. Definitions and ontologies

Overall, most subjects had difficulty when asked how they defined energy, with two people not giving any definition at all. This is not surprising given the complex and abstract nature of this concept. Others made generic statements, such as mentioning the units associated with energy (e.g., “joules”). The most common definition of energy provided was “the ability to do work” (55% of responses), most likely due to the prevalence of this definition in textbooks and instruction. Defining energy as the “force it takes to do work” also appeared in some of the responses (20% of responses). This shows that the concepts of energy and force are not just related to one another, but that they are interchangeable, which is incorrect. This may be due to the fact that over half of the undergraduate subjects had not had physics at the university level yet where formal instruction on forces is much more prevalent than in introductory chemistry. Energy was also defined in terms of a change of some sort (20% of responses). For example, the response “energy is burned or lost or converted in the process” shows that there is some change occurring and that energy is integral to this change.

Some responses were not definitions, *per se*, but more descriptions of the characteristics of energy. This way of talking about energy was mainly seen in the responses from the two experts. For example, a physical chemistry professor said energy was “related to either position or translational energy.” A physics professor described energy as a “way of modeling and describing interactions within a system and/or between a system and surroundings.” Each of these statements emphasizes the utility of energy and its characteristics, more than strictly restating a memorized definition, which shows a deeper understanding of the concept.

The percentage of interviewees whose definitions were consistent with each of the ontologies of energy was calculated (Fig. 1). In general, most subjects referred to energy, kinetic energy, and potential energy as

substances. This was cued through words like “stuff” or “amount.” For example, energy was “the stuff available to do work” or “something you can use to do work.” Defining energy as a force or using verbs such as “do” or “apply” were interpreted as referencing a stimulus ontology. In one response, kinetic energy was defined as “work being applied.” Here, work and kinetic energy are seen as things applied to an object to get it to move, rather than a consequence of the object moving. This also shows that the concepts of force, work, and energy may be conflated in the minds of the interviewees, especially those without previous exposure to physics instruction.

FIG 1. Percentage of definition responses consistent with common energy ontologies. There were zero responses consistent with the vertical location ontology, the combination of stimulus and vertical location, or all three at the same time. The “energy” columns do not sum to 100% because one subject did not provide a definition and another defined energy as a process or model.

Surprisingly, even though all of the subjects have had more formal exposure to chemistry than physics, no one used a vertical location ontology when discussing energy in general. In fact, no one used a combined stimulus and vertical ontology or all three ontologies in any of the definitions for energy, kinetic energy, or potential energy. Diagrams invoking a vertical location ontology are drawn many times throughout a general chemistry course. For example, the bond order or magnetic properties of a homonuclear diatomic molecule are most often determined through a molecular orbital diagram showing the relative energies of the sigma and pi bonding and antibonding orbitals. Similar diagrams are produced for atomic orbitals and can be used for determining ground state electron configurations of atoms or ions. The general format of the question asked (“how do you define the term ‘energy’?”) with no other context specified may lead people to think more broadly rather than to think of specific instances or applications of energy.

Kinetic energy was defined in terms of motion, and potential energy was often defined in terms of location or future outcomes or by contrasting with kinetic energy

(e.g., phrases like “at rest” or “makes it go”). Both kinetic energy and potential energy were more likely to be described as a substance than energy in general. Kinetic energy and its direct connection to motion led to an increase in the use of a stimulus ontology compared to the other terms. Potential energy also saw the most diversity in the ontologies referenced. As with the results on the term “energy,” this diversity may be due to the more abstract nature of potential energy. Possessing multiple views of the nature of energy is consistent with a dynamic ontology view, which is useful in instruction and learning to better apply a more applicable way of thinking in a given situation [5, 6].

B. Word associations

The responses provided during the word association task for the term “energy” ranged over very broad areas (Table 1). Some of the responses related to science in general or general quantities and their units. Others provided answers more specific to domains of science. There were responses that related to biology and life cycles. The physics-related responses centered on specific objects like “batteries” and “springs”. The words associated with chemistry, on the other hand, were less concrete, referencing thermodynamic quantities such as “entropy”, “enthalpy”, “work”, and “heat”. (Like many topics in science, thermodynamics can be considered to be both “chemistry” and “physics”; the distinction is arbitrary. Better understanding what causes students to make these categorizations is the focus of the larger study. Since thermodynamics is a major topic in introductory chemistry, especially the calculation of enthalpy changes, and all of the subjects had previous exposure to chemistry at the college-level, these responses were categorized as “chemistry” rather than “physics”).

People also recognized that energy can be thought of in terms of the kind of energy: “potential” vs. “kinetic” or “chemical” vs. “gravitational”. These responses show a broader applicability than simply mechanical energy, which may be due to many of the subjects’ backgrounds and interests in biology and life sciences.

Energy was also referenced in a more colloquial sense. For example, the words “nuclear” and “electrical” could be referencing either a kind of potential energy or energy as a utility or service, as in “nuclear power”. Words related to action, or the lack thereof, were also prevalent. This usage is reminiscent of the phrase “she has a lot of energy” when used to describe people, which means the person cannot sit still or is always on the move. It may also be related to a deep connection amongst the terms “energy”, “kinetic energy”, and “movement” and the human experience. It is easier to see an object move and associate that with kinetic energy than to see an object remain still and associate that with potential energy. Finally, many words consistent with the abstract nature of

energy were given during the word association task as well. Words like “everything” or “universe” speak to the general nature of energy. The word “stuff” is also connected to the substance ontology. “Universe” and “constant” imply conservation, which is one of the five main characteristics of energy [1, 4].

TABLE 1. Categorization of responses from the word association task for energy.

Category	Provided Words
General scientific terms	Experiments, mass, temperature, force joules, Newton, electron volts, calories, $E = mc^2$
Biology	Sun, life, humans, metabolism, ATP
Physics	Physics, batteries, springs, interaction, light
Chemistry	Electrochemistry, entropy, enthalpy, exothermic, ΔH , work, heat, bond strengths, electrons, reaction coordinate
Kinds	Types, potential, electromagnetic, gravitational, kinetic, thermal, chemical, nuclear, electrical
Everyday use	Nuclear, electrical
Action	Movement, motion, dropping, stationary, ability
Abstract	Stuff, everything, universe, ever-existing

Predictably, the most common words in the kinetic energy words association task related to motion (Table 2). Many of the same types of responses seen for energy were given for kinetic energy: science in general, quantities and units, relation to both microscopic and macroscopic objects, and kinds of energy. Kinetic energy could be “released” or undergo “conversion” (possibly from “gravitational” energy); these words relate to the transformation of energy, another one of the characteristics of energy [1, 4].

Many more words were provided for potential energy than kinetic energy, showing that people have a harder time describing potential energy than kinetic energy (Table 2). As seen in the definitions, potential energy was related to motion by contrasting it with kinetic energy, keyed through words like “stationary” or “at rest”. This suggests that potential energy is thought of as unrealized kinetic energy, rather than its own type of energy. The words associated with potential energy related to the

future more often than with energy or kinetic energy. Many of the responses revolved around the connection between the gravitational potential energy and vertical locations, for example, “heights”, “staircase”, and “roller coaster”. Potential energy was also thought of microscopically, such as its relation to molecular stability and bonding as seen in the use of “bond energies”, “enzyme”, “atoms”, and “molecules”. Again this focus on the stability of molecules and relative bond strengths is an important concept in chemistry and biochemistry and is discussed throughout these courses in various contexts. This manner of thinking and the use of these words in such a context would be expected in chemistry and life science students due to their previous coursework.

TABLE 2. Categorization of responses from the word association task for kinetic and potential energy.

Category	Provided Words
Kinetic Energy	Moving, motion, movement, collisions, never still, rolling, falling, running, swinging, speed, velocity, released, conversion
Potential Energy	Capability, future outcome, pre-movement, impending, stored, stationary, at rest, heights, distance, top high up, staircase, roller coaster, interaction, stability attraction, repulsion, bond energies, enzyme, atoms, molecules, endothermic

IV. CONCLUSION

Volunteers were asked to define the terms energy, kinetic energy, and potential energy as well as perform word association tasks as part of a longer semi-structured interview on the effect of surface features on conceptualizing energy. The responses were coded based on the most common definitions and ontologies of energy. All subjects found defining energy in general to be a difficult task, most likely due to its complex and abstract nature. A majority of novices gave the textbook definition of energy (“the ability to do work”) as their

main definition of the term. Experts, on the other hand, tended to define energy in terms of its characteristics and usefulness, such as emphasizing the conservation of energy. A substance ontology—that energy is a thing that objects can have or possess—was the most common when defining energy, kinetic energy, and potential energy.

The results from the word association tasks show the broad ways in which people think about energy. The most common words associated with kinetic energy were, not surprisingly, related to motion. Those provided for potential energy related to interactions for microscopic objects, locations for macroscopic objects, and future outcomes. Common to all three terms were the units and physical quantities related to energy, which would be used when solving physics and chemistry problems. Other words provided were abstract in nature, which reference important properties necessary when using energy to solve problems in chemistry and physics classes, such as conservation or transformation.

These results are part of a larger study looking at how people understand energy in the domains of both chemistry and physics. Ideally, knowledge of energy from physics instruction should transfer to chemistry contexts and *vice versa*. Future studies will examine the connection between surface features associated with chemistry or physics contexts and the ontologies of energy invoked in the interview responses. Also, explicitly asking interviewees to draw what they think of upon hearing the terms “energy”, “kinetic energy”, and “potential energy” may increase the number of people invoking the vertical location ontology compared to when people are asked to define these terms in words. For example, a current chemistry student may draw an energy level diagram but still define energy in words as “the ability to do work”. This task would provide insight into the effect of representations and would complement those brought forward from the specific figures shown during the interviews. By better understanding how people think about energy in these two domains, curricular interventions can be created to better facilitate the transfer of knowledge between courses in chemistry and physics.

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