Investigating Students' Understanding of Energy Transformation, Energy Transfer, and Conservation of Energy Using Standards-Based Assessment Items

Cari F. Herrmann-Abell and George E. DeBoer
American Association for the Advancement of Science / Project 2061

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Abstract:

Standards-based multiple-choice assessment items were used to study middle school, high school, and university students' understanding of ideas about energy transformation, energy transfer, and conservation of energy. The data are a result of a field test administered to 9739 middle school students and 5870 high school students in 46 states across the country and 176 students from a public university in the south central region of the U.S. Rasch modeling was used to estimate and compare the students' abilities and the item difficulties, and distractor analysis was used to investigate the strength of the students' misconceptions at the different grade levels. Students' performance at each level was used to examine the progression of understanding of energy from middle school to university. The results indicated a grade-to-grade increase in understanding from sixth grade to university, with two exceptions: there was no significant increase in performance between sixth and seventh grade, and there was no significant increase between ninth and tenth grade. The students had the most difficulty with items aligned to the idea of conservation of energy and, in a number of cases, students had more difficulty applying a general principle to a specific real-world case than they did in recognizing the truth of the principle itself.

Introduction:

In today's society, citizens are constantly confronted with a wide range of energy-related issues, such as deciding between purchasing a hybrid or traditional car, and whether or not to unplug electrical devices when not in use. In order to make well informed decisions regarding these issues, all citizens need an understanding of what energy is and how it can be transformed and transferred. In a school setting, energy ideas are central to understanding the life, earth, and physical sciences. If educators have an awareness of how students think about energy, they may be able to diagnose problems in learning in other areas of science that rely on a solid understanding of energy, such as in photosynthesis and respiration, or weather and climate, that might otherwise go undiagnosed. Because energy is an important topic both in and out of school, it is important to have a detailed understanding of what students know and do not know about energy.

Past research on students' understanding of energy has tended to focus on energy as a single unified concept, not on the different "forms" or manifestations of energy. For example, Watts (1983) classified students' ideas about energy into seven alternative frameworks: anthropocentric, depository, ingredient, activity, product, functional, and flow-transfer. Trumper (1990) later expanded on Watts' work by splitting the depository framework into two -- the original passive "depository" framework and an "active" deposit or "cause" framework -- and by adding the transformation framework. Our research probes more deeply into students' ideas about energy by focusing on what students know and think about each individual form of energy. Although we recognize that there is a difference of opinion in the field about whether students should be taught that there are multiple forms of energy or only one form that is manifested in a variety of contexts (Millar, 2005), we have chosen to use the language of "forms" because this language is so widely used in school instruction and because it provides a useful way to organize the various contexts in which energy is observed.

More recently, there have been a number of studies that have investigated learning progressions for the energy topic. Liu and Mckeough (2005) used data from selected items from the Third International Mathematics and Science Study (TIMSS) database. Using the partial credit Rasch model, they demonstrated support for their hypothesized sequence of development of the energy concept. In their proposed progression of understanding, students first perceive energy as activity, or the ability to do work. As students' understanding progresses, they begin to distinguish different energy sources and forms of energy. Next comes an understanding of energy transfer, followed by a recognition of energy degradation, and finally an acceptance of the concept of conservation of energy. Liu and Collard (2005) validated those results in a follow-up study on students in grades 4, 8, 10, 11, and 12 using performance assessments and Many-Facet Rasch measurement. Lee and Liu (2010) found further support for the conclusion that energy conservation was the most difficult for students using 10 two-tiered items based on released TIMSS items addressing energy sources, energy transformation, and conservation of energy. The items were administered to a large sample of middle school students, and the results showed that the conservation of energy items required the highest level of knowledge integration compared to the other two concepts.

Our work builds on and extends the existing knowledge base in a number of ways. First, our study includes a very large national sample of students in grades 6 though 12 (N = 15,609), along with a smaller sample of university physics students (N=176). This gives us a more complete description of how understanding changes from grade-to-grade nationally using a common set of items aligned to the same basic concepts. Second, our assessment items are precisely aligned to specific energy concepts related to energy transformation, transfer, and conservation. This enables us to explore specific problems that students are having with their understanding of these topics. Third, the items are designed to not only test for the correct scientific understanding but also to probe for common misconceptions. This provides the opportunity to make a detailed analysis of the alternative ideas students hold that may be giving them difficulty. In addition, because students who do not understand a concept can sometimes respond correctly to traditional items by guessing or using test-wiseness strategies, incorporating misconceptions into answer choices provides these students with plausible answers to select from so they are less likely to guess, and we get a more valid measure of what they actually know.

The item development process utilizes a procedure for evaluating the items' match to the target science ideas and their overall effectiveness as an accurate measure of what students know about those ideas. During item development, pilot testing is used to obtain written feedback from students about the items. Then scientists and science education experts review the items using a set of criteria to ensure content alignment and construct validity. After revisions are made based on the reviews and student feedback, the items are field tested on a large national sample to determine their psychometric properties.

This paper describes the results from a field test of a set of assessment items aligned to the middle school topic of energy. The paper reports on results from a cross-sectional analysis that was used to investigate the progression of understanding of these ideas from middle school to university and a distractor analysis to examine the differences and similarities in the misconceptions that middle school, high school, and university students hold.

Methodology:

The data reported on here resulted from the field testing of items aligned to ideas about energy transformation, energy transfer, and conservation of energy. The items and results of field testing can be found at http://assessment.p2061.org/. The field test included 9739 middle school students from 297 schools in 40 states and 5870 high school students from 258 schools in 43 states. Additionally, 176 students from a public university in the south central region of the U.S. were tested. These students had taken two semesters of college level physics. Table 1 summarizes the demographic information of the students tested. (Note: It is important to point out that the middle and high school students who were tested were enrolled in a science course but not necessarily a physical science or physics course at the time of testing. Therefore, the high percentage of females does not reflect how many females are actually taking physics courses. Only the university students were actually enrolled in a physics course. Percentages do not add to 100% because of missing data.)

Table 1
Demographic Information for Pilot Test Participants

	Total	Female	Male	Primary Language is English	Primary Language is Not English
Grade	% (N)	%	%	%	%
6th Grade	17.2% (2722)	49.6%	48.6%	88.3%	8.8%
7th Grade	22.4% (3542)	48.9%	49.0%	88.7%	8.7%
8th Grade	22.0% (3475)	49.0%	49.1%	88.6%	8.1%
9th Grade	10.0% (1582)	49.2%	48.7%	88.3%	9.6%
10th Grade	10.4% (1646)	50.4%	47.4%	89.6%	7.0%
11th Grade	10.6% (1667)	51.5%	46.7%	91.3%	6.1%
12th Grade	5.9% (930)	53.4%	45.3%	90.1%	7.6%
University	1.1% (176)	19.9%	80.1%	85.8%	14.2%
Total	100.0% (15785)	49.4%	48.6%	88.8%	8.2%

Because we were field testing more items than students could finish in a typical class period, we created multiple test forms that contained subsets of the items. Each student received 28 to 36 items, and each item was answered by an average of 3215 students. Linking-items allowed us to use Rasch modeling to compare item characteristics across forms. For each item, students were asked to choose one answer, and students who chose more than one answer were marked incorrect.

The ideas on which students were tested are based on the Energy Transformations map in *Atlas of Science Literacy, Volume 2* (AAAS, 2007), and they are consistent with the Physical Science Content Statements in the 2009 National Assessment of Education Progress (NAEP) Science Framework (National Assessment Governing Board, 2008) and the physical science standards in The College Board Standards for College Success (College Board, 2009). The key ideas are:

- *Transformation*: Energy can be transformed within a system.
- *Transfer*: Energy can be transferred from one object or system to another in different ways: by conduction, mechanically, electrically, or by electromagnetic radiation.
- *Conservation*: Regardless of what happens within a system, the total amount of energy in the system remains the same unless energy is added to or released from the system.

Each key idea was further unpacked into sub-ideas that state precisely what students were expected to know and boundary statements that state explicitly what they were not expected to know. These sub-ideas and boundary statements act as item writing specifications that ensure a close alignment between the items and the learning goals. For example, the sub-ideas and boundary statements for conservation of energy include:

Students should know that:

1. Regardless of what happens within a system, the total amount of energy in the system remains the same unless energy is added to or released from the system, even though the forms of energy present may change.
2. If the total amount of energy in a system seems to decrease or increase, energy must have gone somewhere or come from somewhere outside the system.
3. If no energy enters or leaves a system, a decrease of one form of energy by a certain amount within the system must be balanced by an increase of another form of energy by that same amount within the system (or a net increase of multiple forms of energy by that same amount). Similarly, an increase of one form of energy by a certain amount within a system must be balanced by a decrease of another form of energy by that same amount within the system (or a net decrease of multiple forms of energy by that same amount).
4. Energy can neither be created nor destroyed but it can be transferred and/or transformed.
5. If energy is transferred to or from a very large system (or a very complex system), increases or decreases of energy may be difficult to detect and, therefore, it may appear that energy was not conserved.

Boundaries:

1. Students are not expected to quantitatively keep track of changes of energy in a system. This is a later idea.
2. Assessment items will avoid using the phrase "energy conservation" or "conservation of energy" because of the misconceptions associated with them.
3. Students are not expected to know about energy-mass conversions such as nuclear reactions or other subatomic interactions.

In this study, we used Rasch modeling to analyze the field test data. In the dichotomous Rasch model, the probability that a student will respond to an item correctly is determined by the difference in the student's ability and the difficulty of the item (Bond & Fox, 2007). The ability and difficulty measures are expressed on the same interval scale, are measured in logits, and are mutually independent, which is not the case for percent correct statistics. WINSTEPS (Lincare, 2009) was used to estimate the students' abilities and the item difficulties. From these parameters, we were able to determine if the range of item difficulty was appropriate for the students who were sampled and to determine the extent to which each of the items correlated with the entire set of items (point-measure correlation). We also looked to see if the pattern of student responses followed expectations such that the highest ability students were more likely to select the correct answer for an item and the lowest ability students were less likely to select the correct answer. Any discrepancies prompted us to examine the items more closely to determine the cause of the discrepancies and the suitability of the item for future use.

Findings:

The field test data had a good fit to the Rasch Model, suggesting a unidimensional set of items targeting the same basic energy construct. A summary of the fit statistics is shown in Table 2. The separation indices and corresponding reliabilities were high for both the item and person data. The somewhat lower reliability associated with the person separation index (.75) is due to the relatively small number of items available to test students at the extreme ends of the scale, especially the lower end (see Figure 1). This means that there is less information available to measure the ability of low ability students. On the other hand, because there were so many students responding to each item, the difficulty level of the items is easier to determine, which produces a very high item reliability estimate (.99). The infit and outfit mean-square values for all but three of the items were within the acceptable range of 0.7 to 1.3 for multiple-choice tests (Bond et al., 2007).

Table 2:
Summary of Rasch Fit Statistics

	Min	Max	Median
Standard error	0.02	0.09	0.04
Infit mean-square	0.87	1.23	0.99
Outfit mean-square	0.84	1.42	0.99
Point-measure correlation coefficients	0.13	0.5	0.37
Item separation index (reliability)		13.73 (0.99)	
Person separation index (reliability)		1.74 (0.75)	

Figure 1 shows the item-person map for 95 items aligned to ideas about energy transformation, energy transfer, and conservation of energy. The map shows the spread of student abilities on the left side of a vertical line from low ability at the bottom to high ability at the top. Item difficulties are shown on the right side of the line ranging from easiest at the bottom of the map to most difficult at the top. The mean of the item difficulties was fixed at zero. When a student's ability measure matches an item difficulty measure, the student has a 50% chance of answering that item correctly. Student ability and item difficulty are expressed in logits, which can vary from $-\infty$ to ∞. The map in Figure 1 reveals that for these items and these students the mean item difficulty is slightly higher than the mean student ability. Most of the items cluster around the middle range of student ability and there are few items at the lowest and highest ends of the student distribution. The lack of items at the high-ability end of the scale is not surprising because the items were intended to test middle school ideas about energy and we have included higher ability university and high school students in the sample.

Figure 1: Item – person map showing the distribution of student abilities on the left and item difficulties on the right. Item difficulties are shown for 95 items included on the field tests.

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Student ability and item difficulty are expressed in logits. Positive numbers indicate higher ability/difficulty.

Progression of Difficulty by Idea

Table 2 lists the average of the item measures for the energy ideas tested. One-way ANOVA revealed statistically significant differences among the means ($F = 25.907$, $p < .001$). A Bonferroni post hoc test showed that the idea of conservation of energy was significantly more difficult than the ideas about energy transformation and energy transfer ($p < .001$). The difference in average difficulties for the energy transformation and energy transfer ideas is not significant. These results are consistent with previous research.

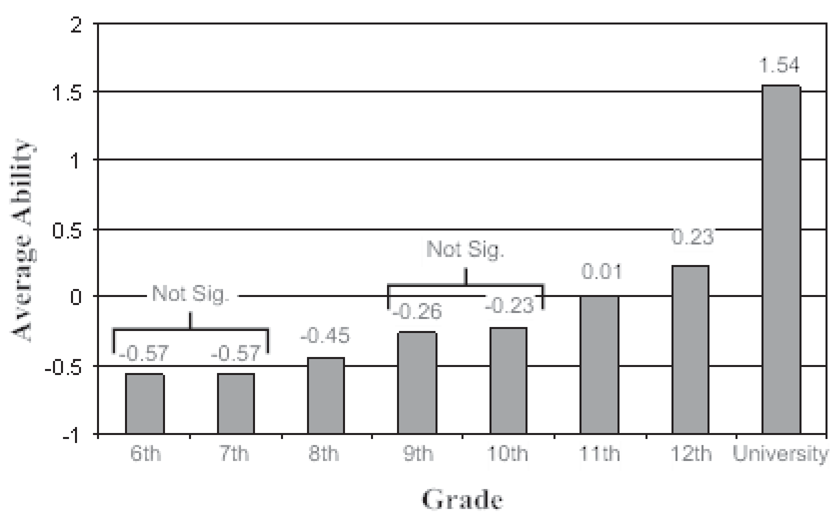
Table 2
Difficulty of Key Ideas as Measured by Field Test Items

		Difficulty			
Field Test Ideas	No. of Items	Min.	Max.	Median	Mean
Energy transformation	24	-0.85	0.66	-0.24	-0.13
Energy transfer	43	-1.35	0.87	-0.23	-0.22
Conservation of energy	28	-0.63	1.67	0.72	0.63

Grade-to-Grade Differences

Figure 2 shows the average ability, expressed in logits, of the students in each of the different grades. One-way ANOVA revealed statistically significant differences in the means ($F = 316.42$, $p < .001$). A Bonferroni post hoc test showed that the differences in mean ability are statistically significant on the .001 level for all grades, except for the differences between sixth and seventh grade and between ninth and tenth grade. This trend of increasing ability with increasing grade level is not surprising given that aspects of the energy topic are typically taught to some extent in each grade. The larger increase between twelfth grade and university students can be attributed both to the greater selectivity of the sample and to the fact that the university students had taken two semesters of university-level physics.

Figure 2: Average Ability by Grade as Measured by Field Test Items



Students' Knowledge and Misconceptions

In this section, we take a closer look at the results of our field test to gain insight into what students know and do not know about energy and what misconceptions they hold. Results from each idea are presented below.

Energy Transformation. Many students in our sample knew that energy can be transformed within a system. The percentage of correct responses to the items aligned to this idea was 42% for the middle school students, 52% for the high school students, and 87% for the university students. Very few students selected answer choices that explicitly stated that energy cannot be transformed (14% middle school, 12% high school, and 2% university).

Student feedback obtained during the pilot test stage of item development provided evidence that some of the difficulties that the students had with the energy transformation items can be attributed to a lack of knowledge about the individual forms of energy (Herrmann-Abell & DeBoer, 2010). To investigate this further, we included items that tested knowledge about the individual forms of energy (e.g. motion energy, thermal energy, gravitational potential energy, and elastic energy) along with ideas about transformation on some of the field tests. The results showed a statistically significant correlation between performance on the forms of energy items and performance on the energy transformation items ($r = .57$, $p < .001$). These results support our hypothesis that knowledge of the individual forms of energy is important for success on items about energy transformation.

Energy Transfer. Items aligned to this idea tested students' knowledge of four different ways energy can be transferred from one system to another. Tables 3 and 4 show the average item difficulties and the percentage of correct responses to these items. The items aligned to ideas about energy being transferred electrically and by electromagnetic radiation were easier than the items aligned to ideas about energy being transferred mechanically and by conduction. However, one-way ANOVA of the item difficulties reveals that the differences in difficulties of these ideas are not significant ($F = 0.826$, $p > .05$).

Table 3
Difficulty of Items Aligned to Different Types of Energy Transfer

		Difficulty			
Type of Energy Transfer	No. of Items	Min.	Max.	Median	Mean
Electrical	2	-0.72	-0.32	-0.52	-0.52
Radiation	10	-1.35	0.87	-0.27	-0.27
Conduction	17	-0.76	0.59	-0.08	-0.10
Mechanical	4	-0.64	0.71	0.02	0.03

Overall, the university students outperformed the high school students, and the high school students performed better than the middle school students (see Table 4). The largest difference between the grade levels was on items testing students' understanding of convection. The smallest gain between grade levels was on items testing ideas about mechanical energy transfer.

Table 4:
Percentage of Correct Responses on Items Aligned to Ideas about Energy Transfer

Type of Energy Transfer	Middle School	High School	University	χ^2	Sig.
Electrical	52%	56%	65%	30.9	< .001
Radiation	43%	49%	66%	174.3	< .001
Conduction	39%	50%	89%	918.7	< .001
Mechanical	39%	42%	49%	18.7	< .001

A closer look at the items aligned to ideas about mechanical energy transfer revealed two difficulties that many students had. First, the misconception that both energy and a force are transferred during a mechanical interaction is widespread at all of the grade levels tested (32% middle school, 43% high school, and 47% university). The misconception that an object has a force within it, or that a force becomes part of an object when it is thrown or hit, has been documented in previous studies (Fischbein, Stavy, & Ma-Naim, 1989; McCloskey, 1983). In our work on the topic of force and motion, we found that middle school students chose this impetus misconception 66% of the time. A similar misconception was revealed by an energy transformation item, where 47% of the middle school students and 45% of the high school students thought that the motion energy of a book that has been shoved across a table is transformed into both a force and thermal energy. Second, many students did not know that in order for energy to be transferred there must be a change in position (the push or pull must act over a distance). About 32% of middle school students, 38% of high school students, and 40% of university students selected the answer choice that states that energy is transferred mechanically whenever one object pushes or pulls on another object even if the objects do not move.

Students also had difficulty with the idea that all objects transfer energy by means of electromagnetic radiation, whether they are in contact with another object or not, especially when the item asks about a real-world context. One item asked students to identify a statement of the general principle of energy transfer by electromagnetic radiation and another asked students to apply this knowledge in the context of hot food. Students at both the high school and university levels did significantly better on the item that required them to identify the general principle than to apply the principle in a real-world situation (for high school students: 43% correct on the general principle vs. 39% correct on the real-world application, $\chi^2 = 11.99$, $p < .001$; for university students: 66% correct on the general principle vs. 45% correct on the real-world application, $\chi^2 = 10.18$, $p < .001$). On the item requiring the application of the general principle to a real-world context, the most popular answer choice stated that energy was transferred only to the things the food is touching (40% middle school, 45% high school, and 53% university). This suggests that although students may have learned that energy in the form of electromagnetic radiation can be transferred between objects even when they are not touching, when asked to apply this knowledge to the real-world example of hot food, they seem to be focused more on conduction than on radiation.

With respect to conduction, the students performed well and showed the most growth from middle school to high school and the university level (see Table 4). Research has shown that one of the most common misconceptions students hold about conduction is that when a cold and a warm object are placed in contact with each other, the warm object gets colder and the cold object gets warmer because "coldness" is transferred from one object to the other (Brook, Briggs, Bell, & Driver, 1984; Newell & Ross, 1996). We tested the prevalence of this misconception in several items. Overall, the misconception was chosen 31% of the time by middle school students and 23% of the time by high school students. University students chose the misconception only 7% of the time. The misconception was particularly strong in situations involving frozen objects. For example, in one item involving an ice pack and a warm can of juice, middle school students chose the misconception that the ice pack transferred coldness to the can of juice 59% of the time, and high school students selected the misconception 46% of the time.

Conservation of Energy. Items aligned to the conservation of energy idea were the most difficult items. The percentage of correct responses to the items aligned to this idea was 28% for the middle school students, 37% for the high school students, and 73% for the university students. However, on an item that involved identifying a statement of the general principle of conservation of energy, 42% of middle school, 56% of high school, and 89% of university students answered correctly. As we found with the radiation example, the results suggest that although many students can recognize the principle of conservation of energy, they are less able to apply it to specific instances. For example, the most difficult conservation items require students to use the idea of conservation of energy to predict the speed of objects. On one of these items, students are asked to predict the speed of a ball after going over a hill on a track in which there is no energy transferred between the track and the ball or between the ball and the air around it. The item requires the students to recognize that because energy is conserved, and because the heights of the track before and after the hill are equal, the ball must be traveling at the same speed. On three items of this kind, the percent correct was 13% for middle school, 19% for high school, and 72% for university. The additional cognitive load involved in interpreting the scenario and drawing logical inferences from it makes these items more difficult than simply recognizing the truth of a general statement about conservation of energy.

Past research has also shown that it is common for students to think that energy can be created or destroyed (Brook & Driver, 1984; Kesidou & Duit, 1993; Kruger, 1990; Loverude, 2004; Papadouris et al., 2008; Stead, 1980; Trumper, 1998). In our sample, distractors involving the creation of energy were chosen 30% of the time by middle school students, 25% of the time by high school students, and 6% of the time by university students. Distractors involving the destruction of energy were chosen 23% of the time by middle school students, 20% of the time by high school students, and 7% of the time by university students.

Conclusions:

This paper describes the results of a field test of items aligned to ideas about energy transformation, energy transfer, and conservation of energy. Overall, we found a trend of increasing ability with increasing grade level through middle and high school to university. We also found that the idea of conservation of energy was significantly more difficult than the ideas of energy transformation and energy transfer. In addition, in some cases, students were more likely to know a general principle than they were to know how to apply that principle to specific instances. The results also showed that some misconceptions about energy are prevalent at all grade levels. For example, students at all grade levels held the misconception that both force and energy are transferred during mechanical interactions. However, the results also showed that many misconceptions decrease in popularity from middle school to university. For example, very few university students thought that "coldness" is transferred from a cold object to a warm object.

Given the wide application of these foundational ideas about energy, it is critical that students understand them and how to apply them in different contexts and that educators understand the persistent nature of misconceptions about energy that many students have. The results of this study can inform and improve science instruction on the topic of energy by revealing what students know about energy, what they can and cannot do with their knowledge, and the misconceptions they have. Because these items are designed to be carefully aligned with the key energy ideas in national content standards but not to any single curriculum or instructional approach, researchers and developers of curriculum materials will be able to compare the effectiveness of various materials and approaches with more precision and objectivity. Use of these items will also allow teachers to accurately diagnose their students' thinking, which will enable them to target instruction more effectively.

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