ASSESSING THE EFFECTIVENESS OF A TOOL FOR CLASSIFYING AND ASSESSING STUDENT ENERGY DIAGRAMS IN PRE- AND POST-COVID-19 INSTRUCTION

By

Michael C. Dudley

B.A. Physics, University of Maine, 2006

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Advisory Committee:

Michael Wittmann, Professor of Physics and Cooperating Professor of STEM Education

MacKenzie Stetzer, Associate Professor of Physics

Franziska Peterson, Assistant Professor of Mathematics Education

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An Abstract of the Thesis
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Energy is a broad concept that is used to interpret and understand scientific phenomena, and appears throughout the Next Generation Science Standards (NGSS) at all grade levels and across disciplines. The NGSS specifies no single approach for energy instruction, and makes use of different energy metaphors, often within individual standards. Gray, et al. (2019) created a checklist (the "Gray Checklist") to identify whether or not a diagram exhibits evidence of core constituent ideas that align to the energy model of the NGSS. This study used the Gray Checklist to find trends in student energy diagrams that were produced during a course of ordinary classroom instruction on energy in two college-preparatory physics classes in the Spring of 2019 and the Spring of 2020.

The Gray Checklist effectively detected fulfillment of energy constituent ideas; however, several trends in the diagrams went undetected by the Checklist. Diagrams tended to show organization along temporal or position-based narrative structures, which implies the importance of building the energy state of objects into energy diagrams. Certain diagrams also broke with

diagramming protocols in order to express energy tracking ideas that the Gray Checklist construes as a violation of conservation of energy. Diagrams also tended to exhibit use of diverse forms of energy in situations not typical of high school energy instruction.

These results suggest changes to the Gray Checklist and implications for teaching and learning regarding energy instruction and the use of energy diagramming schemes in the classroom. Further implications regarding the NGSS and its energy model are also derived from these results. Future work can include creating performance standards for energy diagrams and developing a paradigm of energy as a tool used for modeling rather than a static set of content standards in the NGSS.

“A thousand words will not leave so deep an impression as one deed.”

—Henrik Ibsen

“Dad, energy is something you get out!”

—Meredith Levesque

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CHAPTER 1

BACKGROUND

1.1 On The Purpose and Importance of Standards

The adoption and implementation of comprehensive curricular standards may seem like a modern phenomenon. The Common Core State Standards, for instance, are ubiquitous, and sparked national debate in the United States over whether the alignment of the curriculum in every American school with regard to English language arts and mathematics was essential. In the present day, discussions of the role standards should play in the work of schools, and ultimately, in the day-to-day work of teachers and their students, can be intricate, thorny, and polarizing.

Yet, modern educational standards documents rally around a central cause: in bringing the general population up to speed with a rapidly changing intellectual landscape. For example, the purpose of the Physical Science Study Committee, which established a comprehensive set of curricular goals and materials for teaching physics nationwide, was established in 1956 against the backdrop of the Cold War. Finlay (1962) writes in *The School Review* that the PSSC worked at a time when "science [was] becoming an increasingly consequential factor in the affairs of man," and that physics deserved central treatment as a foundational science. That committee worked to answer the central question of what curricular goals in physics were appropriate for secondary school students in that day and age. In particular, the committee wanted such a curriculum to align with the goal that physics should be a science where the student was an active participant, and that it is an unfinished and evolving human endeavor.

Another example of the central cause of standards documents come from the National Science Education Standards (NSES), published in 1996 by the National Academy of Sciences.

These standards specifically mention the importance of science standards for all students as a matter "of excellence and equity," and that the standards are "premised on a conviction that all students deserve and must have the opportunity to become scientifically literate." (National Research Council, 1996) Underscoring the gravity of this statement, the NSES outlined the nature of that technological and scientific society, one where scientific literacy is essential in every aspect of personal and professional life. Despite this unifying call, the NSES does not prescribe a curriculum, but aims to act as a road map for teachers and administrators upon which curricular decisions can be made. The NSES uses the framework of a road map to "[move] the practices of extraordinary teachers and administrators to the forefront of science education." (National Research Council, 1996)

The Next Generation Science Standards made a similar rallying cry for science education. The NGSS looked to develop a unified, revised set of standards in conjunction with similarly unified standards for mathematics and English language arts. This desire to unify and revise the standards also came from advances not only in science, but also from lessons learned in science education that came about from the implementation of the NSES.

In each of these cases, the work of implementing standards for learning addresses a central problem: how to advance the scientific literacy of the general population of learners. In each case, the approach is slightly different. The PSSC curriculum provided physics teachers with materials, resources, and guidance. The NSES provided a roadmap for curricular guidance. The NGSS revised the map, adjusting for a new understanding of both science and science education. Yet, the standards did not mandate a singular approach; they instead worked to elevate best practices in teaching and learning while setting those practices toward a singular set of goals.

1.2 On The Effect of Standards on Teaching and Research

In the present day, the NGSS may help to point teachers toward curricular objectives and overarching ideas that should be featured prominently in their science classrooms, but it refrains from making prescriptive suggestions for activities aimed at fulfilling those goals. This lack of prescription is parallel to the spirit echoed in the overview of the NSES, where the standards are a tool used to judge whether a particular curricular approach is appropriate for the desired objective. While the intention may be to implore all teachers to do their best curricular work, or to motivate schools and districts to adopt the most effective curricula that can be found, the NGSS makes no specific recommendations on this front. It leaves that decisive work to subordinate groups of educational professionals, even down to the individual instructor.

As a consequence of the guidance given by the NGSS, teachers in any school or district that is subject to public accountability measures must (or, at least, *should*) align their curricular choices to the letter and spirit of the standards. While publishing companies, curriculum coordinators, and department chairs may work to secure or create materials and resources that fulfill standards, it is up to the individual teacher to adopt, revise, supplant, or replace those resources as they see fit for their individual students and circumstances. In the absence of resources, teachers are left to improvise and innovate, filling the vacuum with curricular resources of their own making.

The role of research in this standards-based environment is to help teachers evaluate specific approaches to instruction against the very standards they mean to fulfill. Using data gathered from investigations of these curricular approaches, research can inform professional development meant to improve and streamline approaches that prove initially effective. This

research can also lead to the refinement of future standards to fit new approaches in science instruction and the trajectory of our evolving technological society.

In this thesis, I focus on one particular aspect of the NGSS (instruction about energy in high school physics) and how such instruction can look in the classroom when it includes a particular research-based strategy (energy diagramming schemes). Chapter 2 covers the general landscape of energy instruction and the different ways that diagrams can serve as a centerpiece of this instruction. In Chapter 3, I outline the methods used to study how a particular checklist meant to assess energy diagramming ideas can detect trends in the energy diagrams produced by high school physics students. Chapter 4 contains the summarized results of that analysis, and Chapter 5 lays out implications for teaching and learning, in addition to addressing the central research questions of this thesis. In Chapter 6, I return to the question of how this work fits into the broader picture of energy instruction, and how it affects teachers who ultimately look to meet standards in their instructional work.

CHAPTER 2

INTRODUCTION

2.1 Research Questions and Purpose of Study

Among the Crosscutting Concepts listed in *A Framework for K-12 Science Education* (referred to from here as the *Framework*), a precursor document to the Next Generation Science Standards (NGSS), is *Energy and Matter: Flows, Cycles, and Conservations.* In particular, the *Framework* indicates that the ability to model the behavior of energy in a system is a crucial skill for students at all levels (National Research Council, 2012). However, the *Framework* also acknowledges the complexity and potential for confusion inherent in our own everyday language about energy. In particular, the tendency of elementary school students to identify food and fuel as energy themselves (and not sources of energy) is used as a justification for teaching younger children about cycles of *matter* as opposed to cycles of *energy*, and keeping any further learning about energy for later grades. Yet, for the ubiquitous nature of such a concept throughout science and engineering, and the need expressed to implement standards that are coherent and appropriate to students at their own developmental levels, the energy standards in the NGSS are notably incoherent.

At the same time, physics education researchers have worked to understand energy not just as a simple idea with utility across the sciences, but instead as a series of characterizations that turn the idea from an imponderable one to a ponderable one (Harrer, 2017). While these characterizations are given many names (*metaphor, analogy, ontology,* and others), the purpose of such characterizations is clear: they allow for communication about an abstraction (Daane, Haglund, Robertson, Close, and Scherr, 2018). Several characterizations of the nature of energy

exist: that it is a substance (Scherr, Close, MacKagan and Vokos, 2012; Harrer, 2017); that as a substance it can be stored, transferred, and flow within objects in a system (Brewe, 2011); that it is related to vertical location or a stimulus to action (Scherr, Close, and MacKagan, 2012); and that it is exclusively formless and simply transferred between objects (Nordine, 2019). These ideas are discussed in the context of student work, specifically regarding energy diagrams produced in ordinary classroom instruction, in Chapter 4. Further work in physics education research outlining the need for diagramming schemes in energy instruction are outlined in Chapter 2.4, and specific diagramming schemes that align to these energy metaphors are described in Chapter 2.5.

As the abstract nature of energy lends itself to be described using conceptual language, so too does that conceptual language provide access to energy as an idea with analytical and predictive power in science. Likewise, conceptual language stemming from these bedrock characterizations lend themselves to particular energy diagrams. For instance, Energy Theatre, Energy Cubes, and Energy Tracking Diagrams stem from a substance ontology for energy that allows for energy to flow between objects interacting in a system, to take certain forms, and to transform from one form to another (Scherr, Close, Close, and Vokos, 2012). Pie charts and bar graphs originate from a characterization of energy as being quantifiable, particularly from measurable discrete characteristics such as mass, velocity, and vertical position (Van Heuvelen and Zou, 2000). An Energy Transfer Model relies only on the net energy in an object increasing or decreasing, implying transferability, but neglecting distinct forms (Nordine, Fortus, Lehavi, Neumann, and Krajcik, 2019). Nearly all energy representations rely on a purposeful definition of a *system*: a group of objects interacting together in a physical situation. The establishment of a system of objects relies on another foundational idea: that energy transfer, transformation, and

conservation inherently come from interactions between objects. Chapter 3 highlights these different energy representations and their purpose, and Chapter 4 shows how these representations can look as a product of ordinary classroom instruction.

Recognizing the importance of energy diagramming structures in helping learners communicate about energy and in helping learners use energy as a model for thinking about physical scenarios, Gray, et al., created a checklist that distills the model of energy in the NGSS into discrete criteria for the purposes of evaluating energy diagrams (Gray, Wittmann, Vokos, and Scherr, 2019). The checklist itself uses conceptual language about energy to explicitly link common metaphors and ontologies embedded within the NGSS energy model to specific tendencies in energy diagrams. The checklist is meant to be a tool that can specifically assess what parts of the NGSS model any given diagram exhibits, whether drawn in a previously established format or invented by a learner for a specific purpose or scenario.

The purpose of this study is to use the Gray Checklist to analyze diagrams created by students during a unit on energy taught in a college-preparatory physics class at a medium-sized, independent high school in the Northeastern United States in the spring of 2019 and the spring of 2020. In particular, this study seeks to answer three questions regarding the checklist as a tool for formative assessment:

1. To what extent can the Gray checklist for assessing energy diagrams be used to account for trends in diagrams produced in a high school, college-preparatory physics class?
2. How can the checklist be modified to account for any trends undetected by the checklist, if they exist?
3. How should the checklist differ for the modality of instruction, if necessary?

This study examines data from energy diagrams created by students in two different academic years; the intention was to keep the general modality the same in both classes. The author, also the lead instructor for the course, would supervise the creation of these diagrams in a live classroom as students used them to analyze and interpret varying scenarios in class. While this modality held for the 2019 cohort, the 2020 cohort experienced a substantially different modality in 2020 due to the interruption of live classes brought on by the global COVID-19 pandemic. Furthermore, the lead instructor supervised a student teacher who employed different strategies for instructional delivery, further contributing to a shift in modality for the 2020 cohort. Despite the different modalities, the goal of the study remained the same: to use the Gray checklist to assess student energy diagrams, and in so doing, understand the utility of the Gray checklist as a formative assessment tool in general, for diagrams at any level.

2.2 Theoretical Framework: Energy as a Series of Abstract Characterizations

Before the energy model laid out in the NGSS can be fully defined, it is helpful to define the lexicon through which energy is described. This lexicon is best seen as a series of characterizations of energy; all of the following characterizations are slightly different and serve particular purposes with regard to the formation of ideas about energy. Foundational to these expressions is *conceptual metaphor theory*, which argues that people understand concepts in terms of other concepts. (Lakoff and Johnson, 2008) A *metaphor* is a comparison where two objects that might not otherwise be related are linked by directly using one as a symbol for the other. An *analogy* is a direct comparison of one thing to another, which serves to describe attributes of an abstract object in terms of something more concrete. (Lancor, 2015)

Several conceptual metaphors for energy are used by physicists to discuss its behavior and tendencies in physical systems. These metaphors are *ontological*, in that they describe the

nature of energy as a substance or an entity. A staple metaphor for energy is expressed in Feynman's (1963) lecture on conservation of energy, where energy is likened to blocks that are their own separate, identical, and quantifiable units. Feynman builds on this analogy to include different forms of energy. In this ontological metaphor, energy is expressed as a *substance* that can be possessed by objects, transferred from one object to another, and across system boundaries; as a *stimulus agent* that can cause objects to move or change location; or as dependent on vertical location, where objects that have higher levels of energy are viewed as being located at a higher position than those with lower energy levels. (Scherr, Close, MacKagan, and Vokos, 2012; Dreyfus, Gupta, and Redish, 2015)

Nordine, et al. (2019) propose a different model of energy that conflicts with some of the facets of the substance metaphor. In their model, energy does not exist in diverse forms, but is merely a quantity that exists within a system on account of its conservation, and that it is transferred between objects. This is referred to in later tables and figures as a *systems-transfer metaphor*. This model is proposed specifically to address the conflicting conceptions that students form about energy while learning in a substance metaphor, and to steer them toward scientific consensus about energy. The prominent example of this misconception takes root in the idea that, because humans and other life forms must consume food as a source of energy, that food is energy. A similar misconception is that fuel, such as that put in a vehicle, is energy, as opposed to merely a source of it. The systems-transfer metaphor is meant to realign this misconception with the consensus that it is a matter cycle, driven by chemical or physical changes, that actually link food and fuel to energy production and consumption.

Both sets of conceptual metaphors have several pedagogical advantages. The substance conceptual metaphor allows for energy models where energy *flows between objects* (Brewe,

2011) and can *change forms* while that transfer occurs (Lancor, 2015); the systems-transfer metaphor only accommodates the flow of formless energy between objects. The substance metaphor allows for models to easily account for *conservation*, or the preservation of the total energy throughout a system as an interaction or process occurs. The idea of energy being *lost* or *gained, stored,* and coming from *sources*, also fits the substance metaphor and the systems-transfer metaphor. (Lancor, 2015) Finally, in applications where the energy as substance metaphor does not fit a particular idea (such as the idea of negative energy), the metaphors of energy as substance and energy as dependent upon location can be blended to leverage the pertinent aspects of each. (Dreyfus, Gupta, and Redish, 2015)

The advantage of understanding these conceptual energy metaphors for teaching is that instructors can work to build new metaphors for energy, or students' already existing metaphors for energy, into epistemological resources for further learning. (Daane, Haglund, Robertson, Close, and Scherr, 2018) While having access to solely one metaphor for energy implies that a student's model for energy is incomplete, an instructor knowing several of these models can help students build a more complete picture of energy. (Lancor, 2015)

2.3 The Next Generation Science Standards Model for Energy: Blending Metaphors

The NGSS works to funnel student learning about energy into a unified understanding that involves essential foundations, many of which come directly from the substance metaphor for energy (Scherr, Harrer, Close, Daane, DeWater, Robertson, Seeley and Vokos, 2016). Other foundations for the NGSS model for energy rely on systems-transfer metaphors, such as that proposed by Nordine, et al. (2019). Despite the goal of moving students to a unified understanding, these metaphors are used interchangeably throughout the standards with no discernable, consistent criteria that warrants their application. Tables 2.1, 2.2, and 2.3 illustrate

how these two metaphors for expressing the nature of energy show up in the NGSS: Disciplinary Core Ideas tend to use the substance metaphor for energy more frequently when a simple interaction or energy idea is illustrated (such as that objects can *possess* or *spend* kinetic or potential energy), but tend to use systems-transfer ideas when more complicated energy cycles (particularly those linked to matter cycles). However, the use of multiple energy metaphors within the same standard tends to become more frequent as content gets more complicated in middle school and high school. The high school standards in particular seem to suggest that a high school student might make use of several metaphors for energy over the course of just a few years, where systems-transfer thinking in energy tends to dominate matter and energy cycles, but substance metaphors tend to dominate thinking about simpler system interactions.

An examination of particular standards and how they draw upon the language of energy can reveal how these metaphors align with concrete learning objectives in content and process. Standard HS-PS-3-2 is a terminal standard for energy learning in the physical science standards of the NGSS. The Disciplinary Core Ideas in this standard set out three specific learning targets for students. These targets are for students to understand that energy is a single quantitative property of a system (systems-transfer metaphor) that only exists because of conservation (supported by a substance metaphor), can exist in different forms (substance metaphor), and relies on the relative positions and motions of particles. This standard requires students to adopt a model with a blend of these two conceptual metaphors. Despite this, the Crosscutting Concept in the standard expects students to understand that energy cannot be created or destroyed, and only moves from one object, system, or place to another at a time. This model relies on the substance metaphor, and even implies restrictions and rules that would support an energy-as-entity metaphor. (National Research Council, 2012) That these standards imply a blended model be

implemented in order to achieve all objectives in this standard reflects the complexity of energy learning that is discussed in the *Framework*. (National Research Council, 2012)

Another example of this complexity is in Standard HS-LS-1-5, which involves a discussion of the process of photosynthesis inside of plants. The Disciplinary Core Idea involves understanding that the process of photosynthesis is, at its center, a conversion of light energy to chemical energy within the system of a plant cell. While a systems-transfer metaphor could be sufficient to describe the idea of energy transfers within a system, the presence of forms of energy and the implication of flow that exists in the Crosscutting Concept linked to the standard is supported by a substance metaphor. Other examples of a blended metaphor run throughout the life science standards, from photosynthesis and cellular respiration being sources of energy (substance metaphor) in Standard HS-LS-2-3, to the movement of a more amorphous energy in a food web (systems-transfer metaphor).

It is noteworthy that the blended metaphor consists largely of a substance metaphor that draws upon the systems-transfer metaphor in particular places, particularly in the life science standards. These standards are woven together with objectives that pertain to cyclical matter cycles, such as photosynthesis and cellular respiration. This aligns with the recommendation that such systems should be taught at the high school level, when students are less likely to directly equate energy with matter, such as directly linking food and fuel to energy.

Table 2.1. The NGSS Model of Energy in 4th and 5th Grade physical science standards and underlying metaphors present in both Disciplinary Core Ideas and Crosscutting Concepts.

NGSS Standard	Disciplinary Core Ideas	Crosscutting Concepts	Metaphor Use Within Standard
4-PS3-1: Kinetic Energy	PS3.A: Energy possession is proportional to speed	Energy and Matter: energy transfer between objects	--substance, object to be possessed (PS3.A) --blended (CCC)
4-PS3-2: Light, Sound, Heat, and Electrical Energy	PS3.A: Energy can be moved from place to place PS3.B: Energy is present in moving objects; light transfers energy; electrical currents transfer energy, dissipation transfers energy to air	Energy and Matter: energy transfer between objects	--substance, movable (PS3.A) --blended (CCC)
4-PS3-3: Energy changes when objects collide	PS3.A: Energy can be moved from place to place PS3.B: Energy is present in moving objects; light transfers energy; electrical currents transfer energy, dissipation transfers energy to air PS3.C: In a collision contact forces transfer energy between objects	Energy and Matter: energy transfer between objects	--substance, movable (PS3.A) --exists in explicit forms, can dissipate (PS3.B) --blended (PS3.C, CCC)
4-PS3-4: Test a device that converts one form of energy to another	PS3.B: Energy is present in moving objects; light transfers energy; electrical currents transfer energy, dissipation transfers energy to air PS3.D: Producing energy is releasing it from storage	Energy and Matter: energy transfer between objects	--blended (PS3.B) --substance, storable and movable (PS3.D) --blended (CCC)
5-PS3-1: Food energy was once solar energy	PS3.D: All food energy is solar energy plants and stored until those plants are consumed LS1.C: Food is a source of usable energy	Energy and Matter: energy transfer between objects	--substance, storable and movable (PS3.D) --substance, source (LS1.C) --blended (CCC)

Table 2.2. The NGSS Model of Energy in Middle School (MS) physical science standards and underlying metaphors present in both Disciplinary Core Ideas and Crosscutting Concepts.

NGSS Standard	Disciplinary Core Ideas	Crosscutting Concepts	Metaphor Use Within Standard
MS-PS1-6: Design a device that uses chemical reactions to absorb or release thermal energy	PS1.B: Chemical reactions release and store energy	Energy and Matter: energy flows and can be tracked	--substance, storable and movable, exists in explicit forms (PS3.D) --systems-transfer (CCC)
MS-PS-3-3: Design a device that maximizes or minimizes thermal energy transfer	PS3.A: Thermal energy is the average kinetic energy of particles and depends on types, states, and amounts of matter present PS3.B: Energy leaves hotter areas and moves to cooler areas	Energy and Matter: energy flows and can be tracked	--discrete quantity (PS3.A) --entity that can move (PS3.B) --systems-transfer (CCC)
MS-PS3-5: Support the claim that when kinetic energy changes, energy is transferred	PS3.A: Kinetic energy changes translate to energy changes somewhere else at the same time	Energy and Matter: energy may take different forms	--entity that can change (PS3.A) --substance, exists in explicit forms (CCC)
MS-LS1-6: Explain photosynthesis as a matter cycle and an energy flow	LS1.C: Plants use the energy in light to make sugars, which can themselves be transported and stored	Energy and Matter: matter cycles drive energy flows	--substance, storable and movable (LS1.C) --systems-transfer, linked to matter cycles (CCC)
MS-LS1-7: Food goes through a chemical reaction to be used for other things in organisms	LS1.C: Food is broken down chemically in order to release energy PS3.D: Cellular respiration is a chemical reaction that releases energy	No Crosscutting Concept related to energy listed	--substance, able to be released (LS1.C) --substance, able to be released (PS3.D)
MS-LS2-3: Model the matter cycling and energy flow of the living and non-living parts of an ecosystem	LS2.B: Food webs demonstrate how matter cycles and energy flows through an ecosystem	Energy and Matter: energy flows and can be tracked	--system-transfer, linked to matter cycles (LS2.B, CCC)
MS-ESS2-4: Model the water cycle as driven by energy from the sun and by gravitational potential energy	ESS2.C: The movement of water is driven by the sun and by gravity	Energy and matter: energy flows drive matter cycles	--entity that drives cycles (ESS2.C) --system-transfer, linked to matter cycles (CCC)

Table 2.3. The NGSS Model of Energy in High School (HS) physical science standards and underlying metaphors present in both Disciplinary Core Ideas and Crosscutting Concepts.

NGSS Standard	Disciplinary Core Ideas	Crosscutting Concepts	Metaphor Use Within Standard
HS-PS1-4: Model the release or storage of energy in a chemical reaction as a change in bonding energy	PS1.A: Stable molecules have less energy than their separated atoms, and this much energy will separate a stable molecule PS1.B: Energy stored or released by chemical reactions depends on how bond energies and kinetic energies change	Energy and Matter: energy changes can be understood in terms of energy flows in, out, or within a system	--substance, stored in molecules (PS1.A) --entity, able to separate molecules (PS1.A) --substance, able to be stored and released (PS1.B) --system-transfer, linked to matter cycles (CCC)
HS-PS1-8: Model nuclear reactions and subsequent energy changes	PS1.C: Nuclear processes (fusion, fission, radioactive decay) release energy from, or store energy within, the nucleus	No Crosscutting Concept related to energy listed	--substance, able to be stored and released (PS1.C)
HS-PS3-2: Macroscopic energy is a combination of particle motion energy and energy related to relative position of particles	PS3.A: Energy is a quantitative property of a system that is conserved within a system, continually transferred among parts of a system, and exists in many forms PS3.A: Energy manifests itself as motion, sound, light, and thermal energy PS3.A: Energy is best understood at a macroscopic scale	Energy and matter: energy is conserved	--systems-transfer, referring to a single quantity (PS3.A) --substance-like, exists in explicit forms (PS3.A) --entity that takes other forms (PS3.A) --property of a system (PS3.A, CCC) --blended (CCC)
HS-PS3-3: Design a device that converts one form of energy to another	PS3.A: Energy manifests itself as motion, sound, light, and thermal energy PS3.A: Energy can be converted to less useful forms, such as thermal energy to the outside environment	Energy and Matter: energy changes can be understood in terms of energy flows in, out, or within a system	--entity that takes other forms (PS3.A) --substance or entity that can dissipate (PS3.A) --system-transfer, linked to matter cycles (CCC)
HS-LS1-5: Model photosynthesis in terms of energy conversion	LS1.C: Photosynthesis converts light energy to chemical energy through a chemical reaction	Energy and Matter: energy changes can be understood in terms of energy flows in, out, or within a system	--entity that takes other forms (PS3.A) --substance that can be stored (PS3.A) --system-transfer, linked to matter cycles (CCC)
HS-LS1-6: Model how life elements	LS1.C: As matter and energy flow through living systems, chemical	Energy and Matter: energy changes can be understood in terms of	--system-transfer, linked to matter cycles (LS1.C, CCC)

from sugar form other molecules	elements are recombined and form different products	energy flows in, out, or within a system	
HS-LS1-7: Cellular respiration results in a net transfer of energy through a chemical reaction	LS1.C: As matter and energy flow through living systems, chemical elements are recombined and form different products LS1.C: As a result of these chemical reactions, net energy transfer occurs, releasing the energy needed for life	Energy and Matter: energy is conserved	--system-transfer, linked to matter cycles (LS1.C, CCC) --property of a system (CCC)
HS-LS2-3: Explain the cycling of matter and flow of energy in aerobic and anaerobic conditions	LS2.B: Photosynthesis and cellular respiration are providers of energy for living things	Energy and matter: energy flows drives matter cycles	--substance, source (LS2.B --system-transfer, linked to matter cycles (CCC)
HS-LS2-4: Use mathematical representations to support claims about energy flows and matter cycles in an ecosystem	LS2.B: Food webs demonstrate how matter cycles and energy flows through an ecosystem	Energy and matter: energy is conserved	--system-transfer, linked to matter cycles (LS2.B, CCC)
HS-ESS1-2: Construct an explanation of the Big Bang Theory	ESS1.A: Nuclear fusion produces electromagnetic energy	Energy and matter: energy is conserved	--substance, source, exists in explicit forms (ESS1.A) --property of a system (CCC)
HS-ESS1-3: Explain how stars produce elements	ESS1.A: Nuclear fusion produces electromagnetic energy	No Crosscutting Concept related to energy listed	--substance, source, exists in explicit forms (ESS1.A)
HS-ESS2-3: Model Earth's interior and thermal convection	ESS2.A: Flow of energy is linked to convection within the Earth's core ESS2.B: Radioactive decay adds energy to the Earth's core, driving mantle convection	Energy and matter: energy flows drives matter cycles	--system-transfer, linked to matter cycles (ESS2.A, CCC) --substance, source, exists in explicit forms (ESS2.B)

2.4: Realigning Energy Instruction: The Need for Diagramming Schemes

While the energy model presented in the NGSS poses a set of blended metaphors that work more effectively in different spheres of instruction, the diverse set of metaphors may present a pedagogical landscape that can cause difficulties when students learn about energy in physics instruction.

A primary feature of this pedagogical landscape is the idea that energy can be tightly defined within particular conceptual or mathematical lenses. One example of such a lens is how a force exerted over a displacement might translate to a change in kinetic energy (the "Work-Energy Theorem"). Another example is that work is the ability to transfer energy within a system. Hecht (2019) argues that both of these limited lenses are flawed, and lead to circular definitions of energy that are productive in circumstances that are limited by constraints in tightly defined situations. Chabay, Sherwood, and Titus (2019) point out that most discussions of potential energy do not include the discussion of a two-particle system, which is requisite to that system having a potential energy at all; further, they point out similar inconsistencies with the Work-Energy Theorem and the true energy equation (which takes into account relativistic mass energy) and inconsistencies with the labeling of friction as a non-conservative force which causes energy dissipation in a defined system.

In both cases, the authors propose a reframing of energy ideas as they are taught in modern classrooms. Hecht (2019) proposes a pedagogical realignment of the ideas of matter, force, and energy. This realignment involves a focus on matter and interactions between matter as ways to drive change, which also involves explicitly defining a system. Chabay, Sherwood, and Titus (2019) propose a more explicit treatment of relativistic rest mass and specification of systems of objects. This would allow students to access ideas such as friction and potential

energy from a systems perspective, rather than from the perspective of the individual objects that are affected.

Through this lens for evaluating interactions using energy (which would require explicitly defined systems and interactions), it becomes clearer to see how students struggle with interpreting situations involving energy ideas. For example, Wittmann, Millay, Alvarado, Lucy, Medina, and Rogers (2019) point out the difficulties encountered in middle school instruction when students are asked to answer questions about the behavior of a mechanical system (specifically, a pendulum) and a thermal system (specifically, a frying pan and its surroundings). In their study, students drew upon particular resources about energy transfer that indicated misunderstanding: the idea of energy being "used up" in a system (which ignores its transfer to the outside air) and the idea of "coldness" being responsible for cooling down hot objects. In both cases, the student misunderstandings could be addressed using the pedagogical realignments proposed by Hecht (2019) and Chabay, et al. (2019); a focus on resources that are central to energy (such as the idea that energy reflects changes in a system) can help students come to an understanding of energy that is closer to scientific consensus.

Another example of this evaluation is described by Harrer (2019). In his study, two students use an energy diagramming scheme called an Energy-Interaction Diagram to evaluate which of a pair of billiard balls will arrive at the end of two inclines with different widths first. Harrer illustrates in an example involving two students working on a tutorial with a learning assistant present that the Energy-Interaction Diagram facilitates conversation and evaluation for the students engaging in the problem, and argues for the incorporation of energy diagramming schemes such as that one as a resource for understanding. Further, Harrer argues that the protocols embedded in any energy diagramming scheme allow learners to structure their

disciplinary thinking in order to solve problems; the conversation described by Harrer is an example of how energy diagrams can serve as instructional tools for understanding and using energy as a means for interpreting physical phenomena.

Further work has been done to examine the use of diagrams in problem solving and the indication of the relative value of diagrams to learning specific concepts in physics. For example, Heckler (2010) examines the use of formal and intuitive free-body diagrams in introductory undergraduate physics and the value of those diagrams to problem solving efficacy. Heckler concludes that intuitive diagrams can be more effective for novice learners than the use of more formal diagramming structures when they are engaged in problem solving. While the purpose of this study is not to examine the use of energy diagrams in problem solving necessarily, this dichotomy of formal and intuitive diagramming, and how students can deviate from formal protocol-driven structures into learner-invented structures for diagramming, can be seen in the examples presented in Chapter 4.

These studies are a slice of the work done in the physics education research community regarding diagramming schemes and their benefits in physics instruction. In this study, I focus on assessing two different types of diagramming schemes: formal *protocol-driven* schemes and intuitive, informal *learner-driven* schemes. These schemes are described in further detail in the next section.

2.5 Energy Diagrams: Purpose, Pedagogy, and Alignment to Metaphor

A vast selection of energy diagrams exist, and their purposes are diverse. While a central argument in this thesis will eventually pertain to using any type of energy diagram, this thesis will limit its scope to a few critical energy diagramming schemes used in the instructional settings described in the Methods section.

Energy diagrams allow a learner access to energy metaphors and interpretations through a process of visual representation. Energy diagrams come in two distinct types: *learner-invented diagrams*, in which creators do not follow a specific protocol for their creation, and *protocol-driven diagrams*, in which creators follow an established set of rules, symbols, and interpretive norms in order to achieve a specific goal. While both types of diagrams can be utilized for instruction, each has a specific purpose that allows learners and instructors to make use of them as an instructional tool.

In this study, two specific energy diagramming schemes were utilized for classroom instruction. Here, their purposes, affordances, and leveraged metaphors are described.

2.5.1 Energy Tracking Diagrams and associated schemes

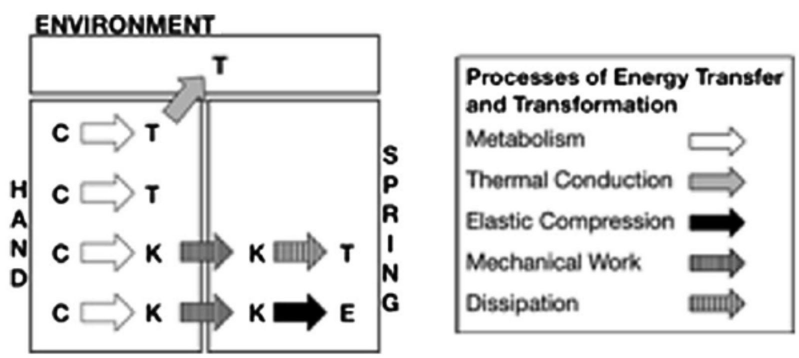


Figure 2.1. An example of an Energy Tracking Diagram for a hand compressing a spring, given by Scherr, Close, Close, and Vokos (2016).

An Energy Tracking Diagram (Scherr, Close, Close, and Vokos, 2012) represents energy within a series of objects in a system. It heavily utilizes a substance metaphor for energy, indicating that the objects with a system possess energy and transfer it among each other in the course of an interaction. The structure of the diagram itself consists of a series of boxes that represent each object, letters that indicate the form of the energy that is possessed by the object, and arrows that are shaded to indicate the mechanism for energy transfers or transformations.

Energy Tracking Diagrams have analogous diagramming schemes that allow for learners to examine energy scenarios using the diagrams rules with manipulatives or kinesthetic action. In fact, Energy Tracking Diagrams are themselves a simplified representation that is derived from their suggested Energy Theatre and Energy Cubes activities. Energy Theater (Scherr, Close, Close, and Vokos, 2012) involves groups of people, each one representing a unit of energy whose form is indicated by a letter formed by the person's hand. Each person moves through regions in their classroom or learning space while energy theatre is going on, in order to process the different energy tracks that a single unit can move through in the course of the interaction. Energy Cubes (Scherr, Close, Close, and Vokos, 2012) is a similar activity, but is suitable for an individual learner; instead of people, units of energy are represented by cubes with several letters that represent common forms of energy. Just as learners in an Energy Theatre scheme move through the activity in scenes, a learner running an Energy Cube activity can move the cubes through spaces on a surface and change the form of the cube by flipping it onto another face.

The purpose of Energy Tracking Diagrams is to teach energy by leveraging the useful aspects of a substance metaphor. In an Energy Tracking Diagram, all energy units must be conserved through the course of the diagram, offering instructors the opportunity to explicitly teach conservation of energy. Energy units must be assigned a form in the diagram, though learners can choose which forms they find pertinent to the situation (i.e., whether thermal energy units ('T's) or kinetic energy units ('K's) are more useful for an object which is going through an increase in temperature as a result of an interaction). The arrows given should be appropriately shaded in order to indicate the nature of the mechanism for which transfer and transformation of energy units occurs. Finally, an appropriate system must be identified, which involves objects pertinent to the interaction and is laid out in a way that allows the learner to draw discernable

energy tracks that best represent the interaction. All of these aspects of the Energy Tracking Diagram come from the metaphor of energy as a substance, one that can be identified and tracked within a system and possessed by objects.

2.5.2 Energy Bars and Energy Pies

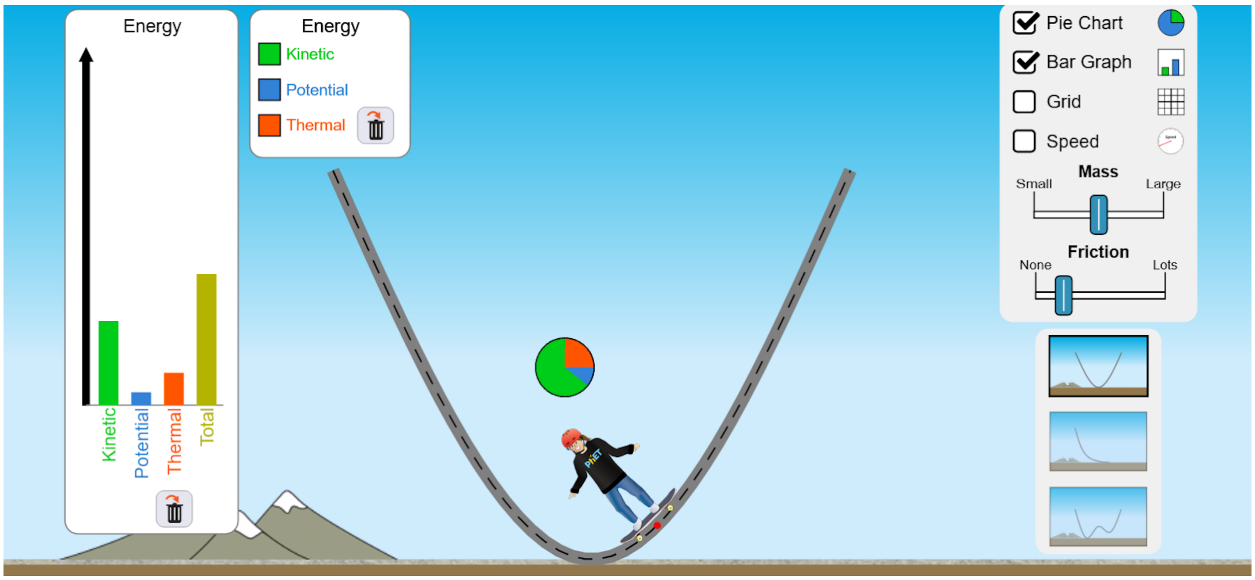


Figure 2.2. A screenshot of the Energy Skate Park simulation (University of Colorado at Boulder, 2020). The use of bar graphs and pie charts to represent the state of the skater as they move through a U-shaped ramp is shown.

The use of bar graphs (called "Energy Bars" in this thesis) and pie charts (called "Energy Pies" in this thesis) as an energy representation speaks to the need to represent energy in discrete quantities, and to represent it as a function of the state of a system. While not a specific energy diagram in its own right, it can be combined with a pictorial representation of a system of objects in order to show how energy changes throughout a system. While Energy Bars or Energy Pies cannot necessarily show explicit units of energy transferring between objects or transformations of those units as they move throughout a system, they can show specific forms of energy and their quantity throughout an interaction. In order for a system of Energy Bars or Energy Pies to do this, a learner may use several Bars or Pies with accompanying pictures of the system and its behavior in order to show how certain quantities change. A representation may also link an

Energy Bar or Energy Pie to the motion of an object in time. For example, the Energy Skate Park simulation published by the University of Colorado at Boulder's Physics Education Technology group, shown in Figure 2.2, illustrates a scheme in which Energy Bars and Energy Pies can be used simultaneously with a moving object in order to demonstrate how certain forms of energy change quantity within a system (University of Colorado at Boulder, 2020). This representation does not make clear how certain units of energy in a particular form change into another form. This overlay of Energy Bars and Energy Pies is referred to in the Results section as an Energy Snapshot; that type of diagram is described in Section 2.5.3.

While Van Heuvelen and Zou (2001) primarily advocate for bar graphs to be used as a tool for improving self-efficacy with physics students who are engaging in problem-solving around energy, they also propose that bar graphs are a part of a broader pictorial scheme that can include pictures of objects moving, graphs of their position, velocity, and acceleration, and other representations that demonstrate an interaction as unfolding over time. This approach is consistent with the presentation of such graphs and charts in simulations like Energy Skate Park. While ideas like conservation, transfer, and transformation are not explicit in these representations, they can be intuited by drawing each of these representations in the right way. For instance, a learner might demonstrate that energy is conserved using a series of Energy Bars if there is a bar indicating that the total energy of the chosen system remains the same. Using Energy Pies, the learner can do this by drawing each Energy Pie the same diameter. Regardless, neither of these forms of energy representation *require* that affordances be made for conservation of energy, energy transfer, or transformation within the system, nor do they necessarily require that a system be defined. (Scherr, Close, MacKagan, Vokos, 2012) They do require the learner to

consider assigning different forms of energy to certain parts of the chart, so as not to create a trivial set of bars or pies that illustrate a single amorphous form of energy.

The pedagogical purpose of Energy Bars and Energy Pies is to help students count units of energy without necessarily forcing them to account for where those units of energy go throughout a system. In order to do this, bar graphs and pie charts loosely use the substance metaphor for energy without adhering closely to every element contained within that metaphor, as an Energy Tracking Diagram does. This allows learners to use bar graphs and pie charts in temporal diagrams of systems without needing to account for all units and their forms, transfers, and transformations, every step of the way.

2.5.3 Learner-Invented Diagrams

A diagram that is created in the absence of a scheme or protocol for creating a diagram is a *learner-invented diagram*, which may take on any sort of form the learner deems necessary in order to complete the diagram. Gray, et al. (2019), in their work analyzing the diagrams created in teacher preparation programs involving energy, identify several distinct types of learner-invented diagrams in addition to their classification of a few specific diagramming schemes. While this list is not necessarily comprehensive, it gives an idea of the common types of diagrams that are likely to come from individual learners as they navigate what an energy diagram means to them.

First, Gray, et al. (2019) observe *energy pictures*, which involves simple diagrams of situations with captions from the learner about where certain types of energy or energy interactions occur. An *energy trajectory* is a flow-chart-like diagram that indicates a path for energy throughout an interaction, even though a system may or may not be defined and the path

may not cover every potential series of changes that energy can take. *Energy source and receiver diagrams* use a similar flow-chart scheme, instead focusing on specific sources of energy and objects in the system that receive that energy throughout the interaction (Gray, Wittmann, Vokos, and Scherr, 2019). In addition, Gray, et al. (2019) classified two different types of *energy snapshots*, which show units of energy as they move through the objects in a system at certain times, and those which specifically mark those energy units with subscripts in order to delineate their uniqueness. Finally, they observe an *energy branching diagram* that is similar to an Energy Tracking Diagram, but with "energy branching" occurring where one unit of energy turns into two, usually in order to change form or to move into two different objects.

In their discussion of Energy Tracking Diagrams, Scherr, et al. (2012) describes similar energy diagrams that fall into three categories of similarity: *energy tracks involving schematics,* where energy is mapped into areas that represent objects; *energy tracks involving pictorial objects,* where energy is mapped onto objects themselves, and *energy snapshots with schematics*, which are abstract areas of a sheet of paper or whiteboard, rather than the objects themselves, where energy units can be placed. While each of the examples given in their discussion retain the core of the Energy Tracking Diagram protocol, their data on learner-invented diagrams that fall under this diagramming scheme reflect similar themes proposed by Gray, et al. (2019): energy diagrams are shown as snapshots, both with and without specific tracking mechanisms like subscripts, uniquely drawn system boundaries, and energy branching.

Both Scherr and Gray describe these learner-invented diagrams in order to highlight the diversity that can result when a learner is asked to make a diagram on their own. Despite the originality of the diagrams they highlight, they also demonstrate that these are similarities that exist between learner-invented diagrams, and they extract some of the same similarities between

diagrams themselves. This indicates that future learners, when tasked with inventing their own diagrams, may come up with diagramming strategies that bear these similarities, which are aligned to common diagrams used in other disciplines (like flow charts). In Chapter 4, student diagrams that align with these similarities are highlighted in the description of the learner-invented diagrams in each set, and they are carefully examined as they relate to each energy prompt.

These energy diagramming schemes reflect the instruction given to the students whose data and diagrams are presented in this thesis, and are meant to give context to their instructional story. While these diagramming schemes were taught in the class described in the next chapter, students used this instruction as a baseline for their work involving energy diagrams, rather than a focus.

CHAPTER 3

METHODS

3.1 Setting and Class Size

The data in this study were collected in the college-preparatory physics classes taught by the PI during the 2018-2019 and the 2019-2020 school years at an independent high school in the Northeastern United States. During the 2018-2019 school year, 19 students were enrolled in the class, and during the 2019-2020 school year, 36 students were enrolled in the class in two separate class periods. This is not necessarily an indication of the size of each data set with regard to completed diagrams; some students did not turn in their diagrams, and others turned in diagrams much later than the assigned date. These diagrams were left out of the data set.

3.2 Instructional Modality and Materials

The curricular setting for the study is a unit on energy which focuses on using energy to interpret, analyze, and make predictions about a wide range of scenarios in physics. In order to process their interpretations and demonstrate their understanding of how energy pertained to each scenario, students were asked to create energy diagrams that reflected each scenario. In both years, students received direct instruction related to the creation of two particular types of energy diagrams: Energy Tracking Diagrams, and energy snapshots with bar graphs and pie charts.

During the 2018-2019 school year, the PI delivered in-person instruction, meeting four or five times a week, depending on the placement of days in a rotating schedule. Classes varied in length between 43-minute and 75-minute periods, each of which were arranged in a 7-period or 4-period day, respectively. Students worked during class time on energy diagrams related to specific prompts which detailed a physical situation. Students were asked to turn in their energy

diagrams as an assignment, which was graded for completion; students were awarded points for that completion, but were not penalized for diagrams that might be classified as incorrect or incomplete. These prompts are listed in Table 3.1. After the conclusion of each class, students uploaded the energy diagrams created in response to the different prompts onto Google Classroom, the preferred learning management system (LMS) for the school. Data from this study were extracted from the LMS and de-identified prior to coding and analysis.

The mode of teaching during the 2019-2020 school year changed after January 2020 on account of a few major instructional shifts. First, a student teacher was assigned to the class, who would serve as lead instructor to the Physics classes under supervision. Second, the COVID-19 pandemic closed schools across the country during the month of March, and in response to the pandemic, the school in which the study took place moved to fully remote instruction for the remainder of the year. This combined two different changes in the same school year: a new student teacher combined with a modality in which students and teachers alike were navigating the dynamics of new online instructional space. Regardless, no curricular changes were made, with fewer prompts delivered over the course of the unit. The prompts delivered to these classes are also listed in Table 3.1; the common prompts that were assigned in both years are also shown.

Table 3.1. A table of the energy diagram prompts assigned to students during the course of the study, along with the academic terms in which the prompt was assigned.

ENERGY DIAGRAM PROMPT	YEARS
#1: On this sheet, draw a diagram that shows the energy transformations that occur when a ball falls down the stairwell under the influence of gravity. Then, draw a second diagram that shows the energy transformations that occur when the same ball is brought back up to the top of the stairwell.	2019 2020
#2: On this sheet, draw a diagram that shows the energy transformations that occur when a ball is carried up the stairwell from the first to the third floor, using a different diagram than you used in Energy Diagram #1.	2019 2020
#3: A penguin starts from rest at the bottom of a slippery Antarctic incline. The incline is made of ice; the surface of the penguin's feet can be approximated to rubber. The penguin begins to walk up the incline, but because of the slippery surface, the penguin is only able to achieve a very slow speed up the incline. The penguin has to keep its feet moving constantly until it reaches the top of the incline. Eventually, the penguin stops at the top of the incline.	2019 2020
#4: A meter stick is bent back from its starting position and it collides with a roll of tape. The roll of tape slides across the floor to a stop.	2019 2020
#5: A pot of water is brought to a boil over an electric stove, and the element is left on. The water continues to boil until all the water is gone.	2019 2020
#6: A bowling ball and a feather fall at the same rate in a vacuum chamber.	2019 2020
#7: A student uses a rope and pulley scenario to pull a 1.0 kg mass from the first floor to the third floor of the school at a constant speed of 0.50 m/s. The 1.0 kg mass starts at rest. The stairwell is 8.8 meters high. When the 1.0 kg mass gets to the top of the stairwell, the student stops pulling and the mass comes to rest.	2019 2020
#8: An Antares rocket is launched from the ground at rest into the upper atmosphere. The escape velocity of the rocket is 11.2 km/s, and the rocket climbs to low Earth orbit.	2019 2020
#9: (Front) A student runs up the stairs. They start from rest and move up the stairs as quickly as they can, coming to rest at the end of the run.	2019 2020
#10: A plane is cruising at constant speed at its cruising altitude.	2019
#11: A car battery powers the lights in a car when the driver leaves them on. The battery eventually dies and the lights turn off.	2019
#12: Draw an energy diagram of any collision in the Mythbusters *Knock Your Socks Off* episode.	2019
#13: A ball falls down the stairwell under the influence of gravity. Then the same ball is brought back up to the top of the stairwell.	2019
#14: A rat trap car with the potential to carry 40.0 J of torsion spring energy has its rat trap fully engaged. The car accelerates under the rat trap's power, fully spends its energy, and brings the car to top speed.	2019
#15: Draw an Energy Tracking Diagram for your rat trap's arm when it is engaged in moving the car.	2019

3.3 Gray Checklist

The Gray Checklist (Gray, et al., 2019) is a list of constituent ideas related to energy that are distilled from the energy standards in the NGSS. An energy diagram can demonstrate these constituent ideas by fulfilling certain criteria linked to each constituent idea. Gray, et al. list ten constituent ideas, each one linked to particular Disciplinary Core Ideas in the NGSS, and composed of their own criteria for fulfillment. Some of these constituent ideas share common criteria, and others possess their own unique criteria. Table 3.2 shows the criteria for fulfillment that were used to evaluate each student energy diagram, and Table 3.3 shows which specific criteria were required to claim that a particular diagram had demonstrated a particular constituent idea.

While Gray, et al.'s (2019) original description of the constituent ideas include a prose summary that describes how each constituent idea might look in a diagram, those criteria had to be distilled into codes that could be applied easily to each diagram for analysis. For the purposes of this study, a diagram needed to show all criteria for fulfillment within a particular constituent idea in order to claim demonstration; diagrams could not "partially" fulfill a constituent idea. For example, fulfilling two out of four criteria in the Transformation of Energy constituent idea did not count as half of the idea being fulfilled. Instead, the Transformation of Energy idea would count as not fulfilled.

The alignment of the Gray Checklist to the NGSS offers instructors and curriculum coordinators an opportunity to align their instructional goals related to energy to certain types of diagrams. Daane, et al. (2018) suggest that building pedagogical content knowledge of the use of implicit metaphors in energy instruction can help teachers throughout the planning process, from identifying the metaphors imbedded in particular energy concepts, choosing activities and

lessons that fit those metaphors, and properly listening and analyzing student discourse for their own use of metaphor with regard to energy learning.

Table 3.2. The thirteen criteria energy diagrams can meet in the Gray Checklist. Fulfillment of certain criteria at once constitute fulfillment of a constituent idea, listed in Table 2.3. Criteria marked with an asterisk are contingent upon fulfillment of criterion A, which specifies that units of energy must be indicated in the diagram, and not simply amorphous quantities, as could be indicated in Energy Bars or Energy Pies through size.

CRITERION AND SUB-CRITERION FOR FULFILLMENT	DESCRIPTION OF CRITERION
A: Units or Quantity	Explicit quantities or units of energy are shown in the diagram.
B: Consistent Quantity	The same quantity of energy, or the same number of units of energy, are shown throughout every stage of the diagram.
C: Movement (Can be specific to fields, objects, or defined systems.)	Energy is shown going from one place to another. Energy can be shown moving to or from a field, a particular object, or a defined system.
D: Change	Energy experiences transfers and/or transformations throughout the interaction.
E: Forms	Specific forms of energy are depicted in the diagram.
F: Observables	Observable quantities go with the specific forms of energy pictured throughout the diagram (for example, mass and speed are shown with kinetic energy).
G: Units Change*	Units themselves change from one form to another in the diagram.
H: Unit Location* (Units can be located in an object, field, or system.)	Units are located somewhere in the diagram, whether within an object, field, or system.
I: Mechanism Shown	Mechanisms for energy transfer or transformation are shown in the diagram.
J: System Boundary	A system boundary is shown in the diagram over which energy might cross.
K: Spread	Energy spreads from one object to multiple objects over the course of the diagram.
L: Usefulness	Energy is shown "doing something" in the diagram. (*Gray, et al. indicate that this is not part of the diagram itself.*)
M: Discrete Calculations	Energy is linked to specific formulae or calculation in order to find its quantity. (*Gray, et al. indicate that this is not part of the diagram itself.*)

Table 3.3. The ten constituent ideas of the Gray Checklist. The descriptions of each constituent idea are those given by Gray, Wittmann, Vokos, and Scherr (2019); the criteria for fulfillment are compressed into codes based on Gray, et al.'s description of how the constituent ideas might appear in a diagram.

CONSTITUENT IDEAS	LINKED CRITERIA FOR FULFILLMENT
Conservation of Energy: The number of energy units remains constant throughout a scenario.	A: Explicit Quantity or Units B: Consistent Quantity of Units
Tracking of Energy: Energy may be tracked by following its path among objects, fields, and systems.	A: Explicit Quantity or Units C: Movement D: Change
Forms of Energy: Energy manifests in multiple forms throughout a scenario.	E: Forms
Observables: Forms of energy are indicated by observable quantities (i.e. temperature is indicated by thermal energy).	E: Forms F: Observables
Transformation of Energy: Energy can transform from one form to another.	A: Explicit Quantity or Units D: Change E: Forms G: Units Change
Transfer of Energy: Energy can move from one object or field to another.	A: Explicit Quantity or Units D: Change H: Location
Mechanism: Energy transfer occurs through specific mechanisms or processes.	C: Movement I: Mechanism Shown
System: A collection of relevant objects in a scenario are defined by a boundary that energy may cross.	C: Movement J: System Boundary
Spread: Uncontrolled systems evolve toward more even energy distribution.	C: Movement K: Energy in More Objects
Usefulness: Some forms of energy are more or less useful than others (i.e. thermal energy lost to the environment is less useful than thermal energy doing work).	L: Energy Put to Work
Mathematization: The amount of energy associated with observable quantities and object properties can be expressed mathematically.	F: Observables M: Discrete Calculation

While the Gray Checklist comprehensively covers all constituent ideas that are either explicitly or implicitly stated in the NGSS, this study focused on specific constituent ideas that matched the instructional goals of the curriculum and the energy standards that might be fulfilled in a regular high school physics environment. The checklist can flexibly allow for evaluation of diagrams for their fulfillment of certain constituent ideas using the same baseline criteria. To that end, student diagrams were evaluated against seven constituent ideas in the Gray Checklist: conservation, tracking, forms, transformations, transfers, mechanisms, and system boundaries. Other constituent ideas were left out of the evaluation of the data. For instance, while students illustrated the idea of energy dissipation in their diagrams, the constituent idea of Spread, which directly addresses how energy moves into an even distribution across a defined system, was not a central focus of the unit. The means through which the Gray Checklist is used to make this evaluation is described in Section 3.5.

3.4 Choice of Diagrams for Assessment

While all diagrams could feasibly be analyzed by using the Gray Checklist, only the diagrams from certain prompts were chosen. Specifically, diagrams from the beginning, middle, and end of the instruction were chosen, in order to investigate student progress from the beginning of the energy unit each year to the end. These chosen prompts also were meant to reflect a diverse set of scenarios, in order to illustrate the utility of the Gray Checklist and of energy diagrams as a curricular tool. Finally, and most importantly, each prompt chosen was used for instruction in both the Spring of 2019 and the Spring of 2020, in order to compare the results of the analysis across changes in instructional mode and environment.

Energy Diagram #1 (Ball Falling Down a Stairwell) was given as an initial energy diagramming scenario at the beginning of the energy units in both school years. Meant as a

pre-assessment, students were asked to respond to this prompt by drawing any energy diagram that came to mind, not just focusing on a specific energy diagram format. In the Spring of 2019, students completed this diagram with no access to their phones, or to computers. In the Spring of 2020, due to the nature of the learning environment, students were assigned Energy Diagram #1 outside of “live” class time, and therefore were allowed to complete the assignment at their leisure and with any resources they could find.

Energy Diagram #5 (Pot of Boiling Water) was given in the middle of the energy unit in both semesters. This energy prompt marks a dramatic shift in typical high school energy instruction, which usually focuses on mechanical energy; the NGSS indeed places a heavy emphasis on mechanical energy in its high school energy standards (National Research Council, 2012). Up to this point in both units, the focus was indeed on mechanical energy. This prompt, which asked students to investigate both bringing the pot of water to a boil and the evaporation of the water into the outside environment, was an opportunity for students to explore a complex system of objects, and to make a variety of deliberate system choices that could potentially change their interpretation of how energy was transferred throughout the system. Furthermore, the energy prompt is a chance for students to demonstrate their ability to use several parts of the energy model in their explanation: choosing the right forms of energy to describe the scenario, demonstrating how transfer and transformation either does or does not occur during the boil, and showing that energy dissipates into the outside environment in some fashion.

Energy Diagram #9 (Student Running Up Stairs) was the last energy prompt given to both cohorts of students. This energy prompt was delivered in different ways for each cohort. In the Spring 2019 cohort, this energy diagram followed an activity entitled “Find Your Horsepower”, where students completed a calculation of their own rate of energy expenditure

based on measurements taken as they either walked or ran up a flight of stairs during in-person instruction. In the Spring 2020 cohort, students were simply asked to imagine the activity in order to complete the diagram, but the activity of finding the rate at which they expended energy was not completed. This activity signaled a return to mechanical energy in the curriculum, with the goal of including forms of energy that might have been included in energy prompts like the Pot of Boiling Water, such as thermal energy. The pedagogical aim of such an inclusion was for students to recognize the production of thermal energy during contact interactions between objects (for example, friction between surfaces moving past one another).

In all three cases, students were asked to complete energy diagrams for the prompt. In the Ball Falling Down a Stairwell prompt, students were asked to draw any diagram that came to mind. In the Pot of Boiling Water prompt, students were specifically directed to draw an Energy Transfer Diagram, as the instruction had begun to focus on both these types of diagrams and instruction on the requisite parts of the energy model necessary to access that particular diagram. Finally, in the Find Your Horsepower prompt, students were instructed to draw different diagrams in different years. Students in the Spring 2019 cohort were asked to draw Energy Tracking Diagrams specifically, while students in the Spring 2020 cohort were asked to draw whatever diagram came to mind.

Toward the end of each term, students were also asked to give their best definition of energy as a reflection of their learning at the end of the energy unit. These written explanations were assigned as a free write. In the Spring 2019 cohort, students worked alone or in pairs to come up with a definition of energy; in the Spring 2020 cohort, students turned in the prompt on their own. The purpose of this prompt was to identify what metaphorical language students used to describe energy after their experiences working with energy diagrams. These written

reflections were assigned after the completion of Energy Diagram #14 in the Spring 2019 cohort and after Energy Diagram #9 in the Spring 2020 cohort.

3.5 Coding and Analysis

After all data were collected, diagrams produced in response to chosen prompts were evaluated using the Gray Checklist as it is presented in this chapter. First, each individual student diagram in a particular assignment batch was coded for the individual criteria that they fulfilled; criteria that did not fall under the preferred constituent ideas for the analysis were left out of the data set. After each diagram was coded for these criteria, the criteria data were used to determine whether or not each diagram met the chosen constituent ideas. In order to interpret these codes, benchmarks needed to be established for different classes of diagrams that were produced by students.

For Energy Tracking Diagrams and Energy Bar/Energy Pie representations in particular, the features of the diagrams require adherence to certain constituent ideas in the Gray Checklist. These designated constituent ideas serve as benchmarks for whether a specific diagram in the data set meets the criteria required when drawing the diagram. Specifically, while Energy Tracking Diagrams have specific rules built into them that align with the constituent ideas (for instance, that the same number of energy units are trackable throughout every stage of the diagram, thus obeying the constituent idea of conservation of energy), a student may make omissions that make this tracking unclear.

In addition to the Energy Tracking Diagrams and Bar Graph/Pie Chart representations that were created, this list of benchmarks served as an evaluation tool for any learner-invented diagrams that were produced. This is especially important at the beginning of the instruction, in

order to highlight the potential constituent ideas that are represented by learner-invented diagrams. While students were not prompted to follow a protocol for these diagrams, evaluating these diagrams against benchmarks could offer insight into students' initial energy models, either from their own previous learning or from their own raw intuition.

It is important to note that each of the different representations *can* demonstrate the criteria necessary for achievement of a certain constituent idea. Regardless of the protocol driving the creation of the diagram, the analysis evaluates each diagram against these chosen constituent ideas in order to determine their curricular effectiveness. The data in the following chapter comes from the use of this checklist in order to understand the trends students exhibit when creating diagrams in response to the prompts in the curriculum.

CHAPTER 4

RESULTS

In this section, the attributes of the student energy diagrams analyzed in this study are described. The description of the data is in chronological order, starting with the energy prompt assigned first in the unit and ending with the energy prompt assigned last in the unit. Dates on which the assignments were given illustrate the different timelines in which the instruction and assessment occurred. The results include the Gray Checklist criteria that each diagram fulfills, and the constituent ideas that each diagram demonstrates as a result of meeting specific criteria. If a particular set of diagrams contains no instances of the fulfillment of a criterion, that criterion is left out of the data table completely. For instance, several diagrams do not indicate any mechanism for interactions. Criterion I (Mechanism Shown) is left out of some data tables for this reason.

4.1 Energy Diagram #1: Ball Falling Down a Stairwell

Energy Diagram #1, which asks students to draw energy diagrams of any type about a ball falling down a three-story stairwell located in their school, was assigned to the Spring 2019 cohort on March 8, 2019, and to the Spring 2020 cohort on May 7, 2020. This prompt served as the introductory energy prompt for both cohorts, and gave students the opportunity to draw what came to mind for an "energy diagram."

4.1.1 Spring 2019 Cohort Data

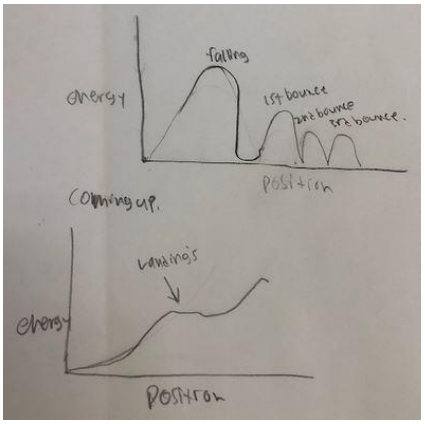
Energy Diagram #1 was completed by 19 students in the Spring 2019 cohort. In this particular prompt, 18 out of 19 students completed a learner-invented diagram that did not resemble any particular energy diagram. One student in the cohort drew an energy diagram that

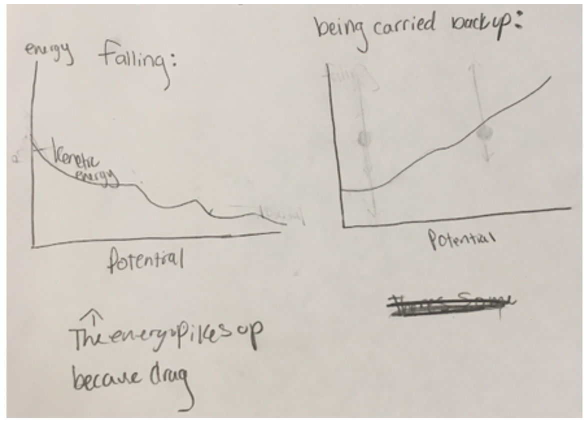
resembled an energy source/receiver diagram, which is a flow-chart like diagram indicating energy flow from object to object in an interaction. Table 3.1 illustrates how the 19 learner invented diagrams broke down in terms of makeup.

Table 4.1. A breakdown of the learner-invented diagrams produced by the Spring 2019 cohort in response to the Ball Falling Down the Stairs prompt.

DIAGRAM TYPE	NUMBER OF DIAGRAMS (N = 19)
Line Graph: A diagram with vertical and horizontal axes that depicts an energy amount, presumably of a particular amount with regard to time	12 (63%)
Energy Trajectory: A diagram that depicts the path energy might take throughout a system; this diagram does not necessarily track individual units throughout the system	4 (21%)
Energy Snapshot: A diagram that shows pictures of the energy state of a system at different points in time	2 (11%)
Energy Source/Receiver: A diagram that depicts an energy trajectory in terms of sources of energy and receivers of energy (described by Gray, et al. (2019)).	1 (5%)

A clear majority of the students produced an energy diagram that featured only a line graph. The content of these line graphs varied, but generally followed a clear link to vertical position (i.e., the line in the graph was decreasing as the graph was read to the right), or to the perceived value of the potential energy in the system. Examples of line graph diagrams in this prompt are shown in Figure 4.1 and Figure 4.2.





Figures 4.1 and 4.2. Examples of line graph learner-invented diagrams as responses to the Ball Falling Down an Stairwell prompt in the Spring of 2019.

Four students in the Spring 2019 cohort produced energy trajectories, indicating a path that energy might take as it moved through a system, whether that system was explicitly defined or not. The makeup of these energy trajectories varied, and did not necessarily follow a specific pattern. An example of an energy trajectory diagram for this prompt is shown in Figure 4.3.

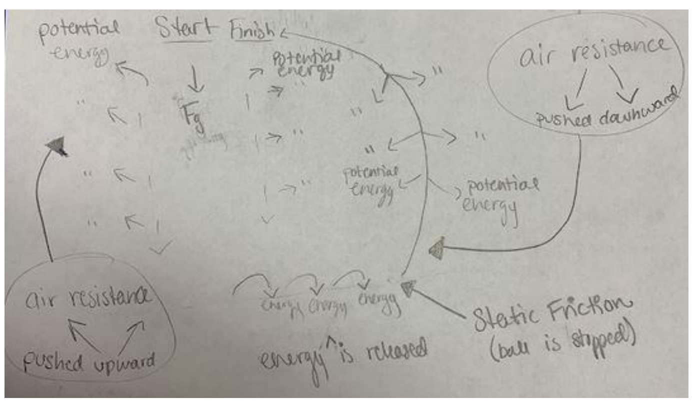


Figure 4.3. An example of a learner-invented energy trajectory diagram as a response to the Ball Falling Down a Stairwell prompt in the Spring of 2019.

Two students in the Spring 2019 cohort produced energy snapshot diagrams, which are descriptions of the energy state of the system (usually shown through a quantitative representation like an Energy Bar or an Energy Pie) imposed onto a pictorial representation of the physical state of the system. These learner-invented energy snapshots included some form of

quantitative analysis, such as formulae or numerical estimates of the energy of the system. An example of an energy snapshot diagram for this prompt is shown in Figure 4.4.

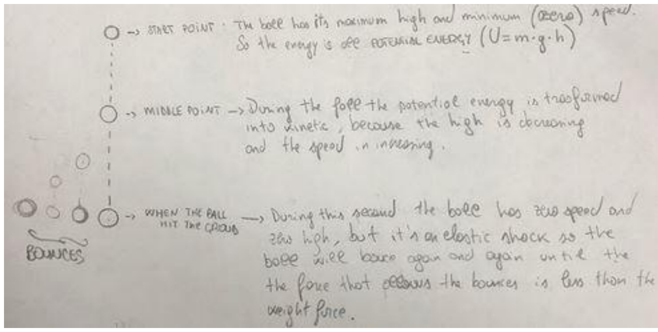


Figure 4.4. An example of a learner-invented energy snapshot diagram as a response to the Ball Falling Down a Stairwell prompt in the Spring of 2019.

Finally, a sole Energy Source/Receiver diagram was produced in the Spring 2019 cohort. This diagram is similar to an energy trajectory, but rather focuses on the specific forms of energy that move from an initial "source" to subsequent "receivers", possibly undergoing transformations in the process. This energy source/receiver diagram is shown in Figure 4.5.

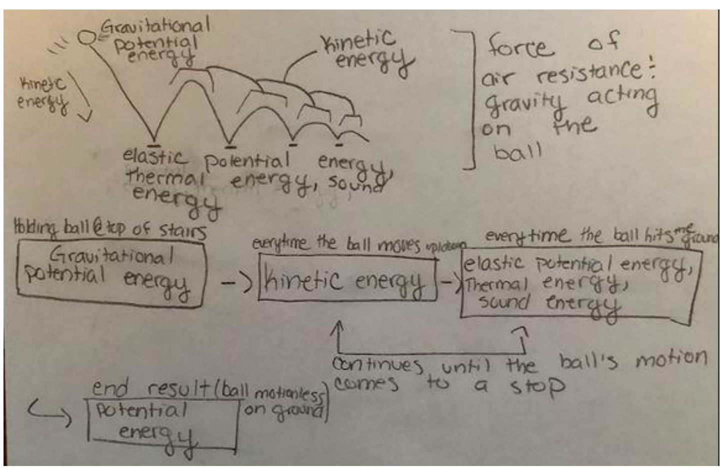


Figure 4.5. The sole learner-invented energy source/receiver diagram as a response to the Ball Falling Down a Stairwell prompt in the Spring of 2019.

In order to determine how many constituent ideas these diagrams demonstrated, each one was first evaluated using the criteria in the Gray Checklist. The results of that evaluation are

listed in two separate tables: one table (Table 4.2) shows the criteria fulfilled by the whole class as an aggregate, and the other (Table 4.3) breaks down the criteria fulfilled by diagram type.

Table 4.2. Criteria fulfilled by the diagrams created by the Spring 2019 cohort in response to the Ball Falling Down a Stairwell prompt.

CRITERION FOR FULFILLMENT	DIAGRAMS FULFILLING CRITERIA (N = 19)
A: Units Or Quantity	0 (0%)
B: Consistent Quantity	0 (0%)
C: Movement	1 (5%)
D: Change	1 (5%)
E: Forms	16 (84%)
G: Units Change	0 (0%)
H: Unit Location	0 (0%)
I: Mechanism Shown	1 (5%)
J: System Boundary	0 (0%)

Table 4.3. Criteria fulfilled by diagrams created by the Spring 2019 cohort in response to the Ball Falling Down a Stairwell prompt, broken down by type.

DIAGRAM TYPE	CRITERIA FULFILLED
Line Graph (12 diagrams)	E (Forms): 11 (92%)
Energy Trajectory (4 diagrams)	C (Movement): 1 (25%) E (Forms): 3 (75%)
Energy Snapshot (2 diagrams)	E (Forms): 1 Of 2 (50%)
Energy Source/Receiver (1 diagram)	D (Change) E (Forms) I (Mechanism Shown)

These initial diagrams only fulfilled one constituent idea in general: the Forms idea. While it is possible that students have an awareness of other constituent ideas (such as energy conservation) from previous classes, demonstration of these ideas through the diagram was not indicated by the Gray Checklist. A full breakdown of the constituent ideas demonstrated by the diagrams is given in Table 4.4.

Table 4.4 Constituent ideas fulfilled by diagrams created by the Spring 2019 cohort in response to the Ball Falling Down a Stairwell prompt. The requisite criteria for demonstrating each constituent idea are also shown.

CONSTITUENT IDEA	DIAGRAMS FULFILLING CONSTITUENT IDEAS (N = 19)
Conservation (A, B)	0 (0%)
Tracking (A, C, D)	0 (0%)
Forms (E)	16 (84%)
Transformation (A, D, E, G)	0 (0%)
Transfers (A, D, H)	0 (0%)
Mechanism (C, I)	0 (0%)
System (C, J)	0 (0%)

These results indicate a dominant model of energy that is consistent with what is taught in previous grades according to the NGSS. Students in this class include using multiple forms in their model for energy, yet demonstrate no other energy metaphors through their diagrams. The dominance of line graphs as a diagramming scheme suggests that quantification of energy may also be a facet of their energy model, but all of the line graph diagrams lacked graduated axes, so this element of the energy model is not explicit.

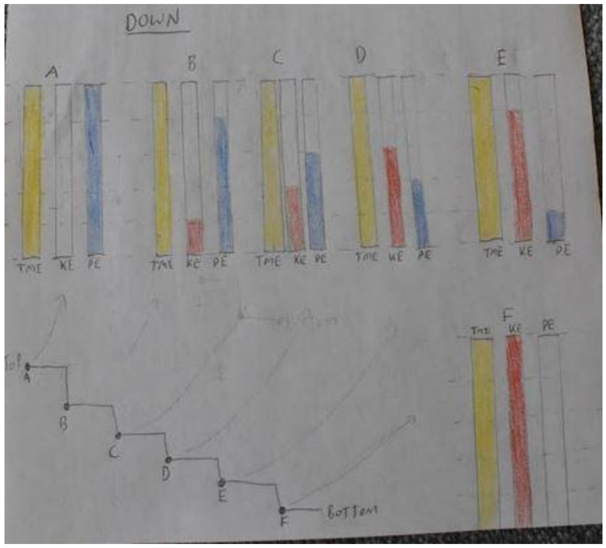
4.1.2. Spring 2020 Cohort Data

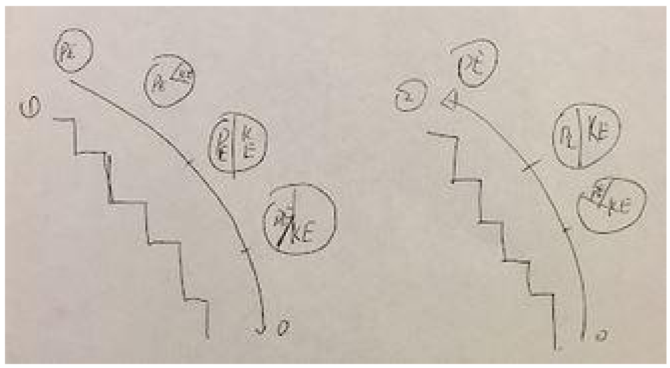
Energy Diagram #1 was completed by 33 students across two different class periods in the Spring 2020 cohort. Completion of this prompt yielded much different results than those of the Spring 2019 cohort. The Spring 2020 cohort completed diagrams of greater diversity, and used diagramming approaches that follow structures with increased rigidity. Furthermore, the diagrams were multi-dimensional on a more frequent basis, using more than one technique to demonstrate the energy states of the system. Table 4.5 gives a full breakdown of the types of diagrams drawn by the Spring 2020 cohort; the diagrams may have fallen into more than one of the listed types.

Table 4.5. A breakdown of the types of diagrams produced by the Spring 2020 cohort in response to the Ball Falling Down the Stairs prompt.

DIAGRAM TYPE	NUMBER OF DIAGRAMS (N = 33)
Energy Pies: A diagram with one or more pie chart diagrams showing the energy state of a system, usually imposed onto a pictorial representation of the behavior of the system	14 (42%)
Energy Trajectory *(described in Table 4.1)*	10 (30%)
Energy Snapshot: A diagram that shows one or more moments in time during the behavior of the system, so that the energy state of the system at that time can be shown	11 (33%)
Energy Bars: A diagram with one or more bar graph diagrams showing the energy state of a system, usually imposed onto a pictorial representation of the behavior of the system	4 (12%)
Energy Source/Receiver *(described in Table 4.1)*	4 (12%)
Energy Flow Diagram: A diagram that uses a series of interconnected arrows, each with different widths, to describe the flow of energy throughout a system	2 (6%)
Free-body Diagram: A representation of the forces on an object	1 (3%)

While no particular energy diagram format dominated, the diagrams produced by the Spring 2020 cohort are demonstrably more diverse and follow formats with more structure. The breakdown in Table 4.5 also does not indicate the intersections between diagrams.





Figures 4.6 and 4.7. Examples of Energy Bars and Energy Pies diagrams produced by the Spring 2020 cohort in response to the Ball Falling Down a Stairwell prompt. Both diagrams shown are also Energy Snapshots, where each set of Energy Bars or Energy Pies indicate the energy state of an element of the system in time.

A plurality of the students in the Spring 2020 cohort drew an Energy Snapshot diagram that included either Energy Bars or Energy Pies in order to show the energy states of the system at certain moments in time. Eleven diagrams were Energy Snapshots, and all Energy Snapshot diagrams included either Energy Bars or Energy Pies. Four Energy Pies diagrams and one Energy Bars diagram did not employ an Energy Snapshot strategy.

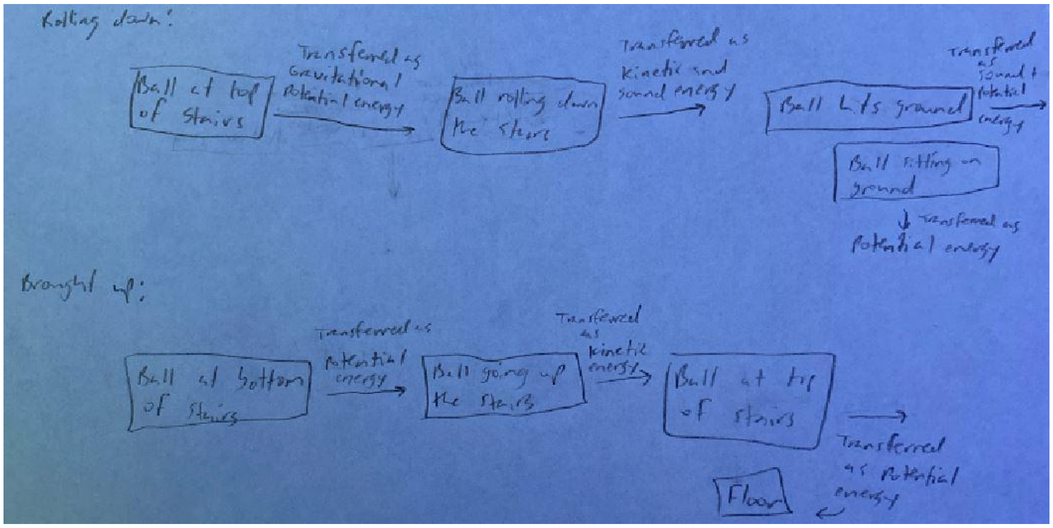


Figure 4.8. An example of an Energy Trajectory diagram produced by the Spring 2020 cohort in response to the Ball Falling Down a Stairwell prompt.

Ten students drew Energy Trajectory diagrams that typically were presented as standalone descriptions of how energy moved through the system. Some of these diagrams (like the example shown in Figure 4.8) show the idea of energy being stored and spent in certain places, yet few of them indicated different forms of energy in the trajectory itself.

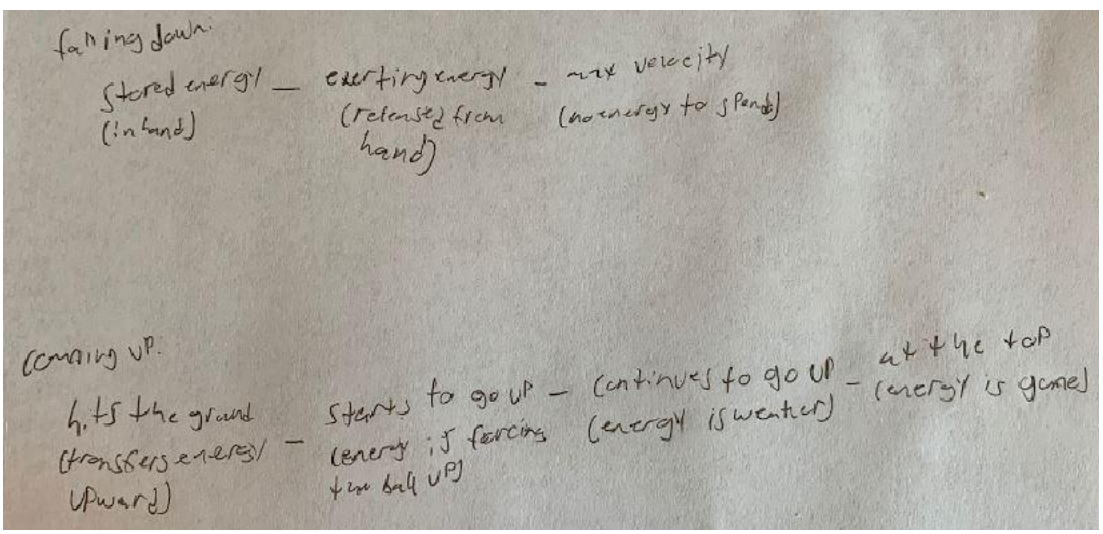


Figure 4.9. An example of an Energy Source/Receiver diagram produced by the Spring 2020 cohort in response to the Ball Falling Down a Stairwell prompt.

Four students drew Energy Source/Receiver diagrams, all similar to the singular Energy Source/Receiver diagram drawn in the Spring 2019 cohort.

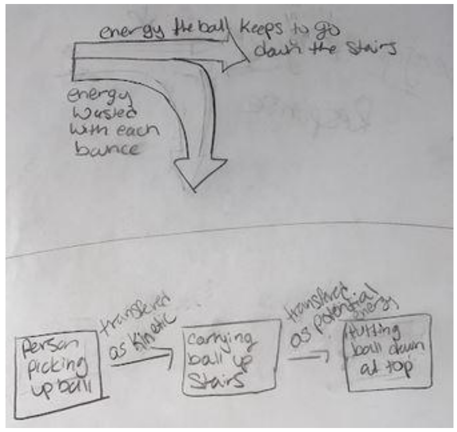


Figure 4.10. An example of an Energy Flow Diagram produced by the Spring 2020 cohort in response to the Ball Falling Down a Stairwell prompt. This diagram accompanies an Energy Trajectory diagram.

One example of the two Energy Flow Diagrams created by the Spring 2020 cohort is listed in Figure 4.10. In this diagram, the width of the arrows indicates relative quantities of energy in the system, and the width of arrows that diverge from the initial main arrow is an indication of how much energy has moved to other elements of the system. In both Energy Flow Diagrams, it is implicit that the diagram is meant to represent the ball, and that energy eventually leaves the system through bounces, or through the process of falling (which signifies changes from potential to kinetic energy).

Finally, one student in the Spring 2020 cohort drew a Free-Body Diagram for their energy diagram. An example of one of these Free-Body Diagrams is shown in Figure 4.11. While not an energy diagram itself, a Free-Body Diagram shows mechanisms for interaction. Regardless of this, it does not meet criteria I (Mechanism Shown), as information about the transfer or transformation of energy within the system does not accompany the information that the Free-Body Diagram gives about the nature of the interaction.

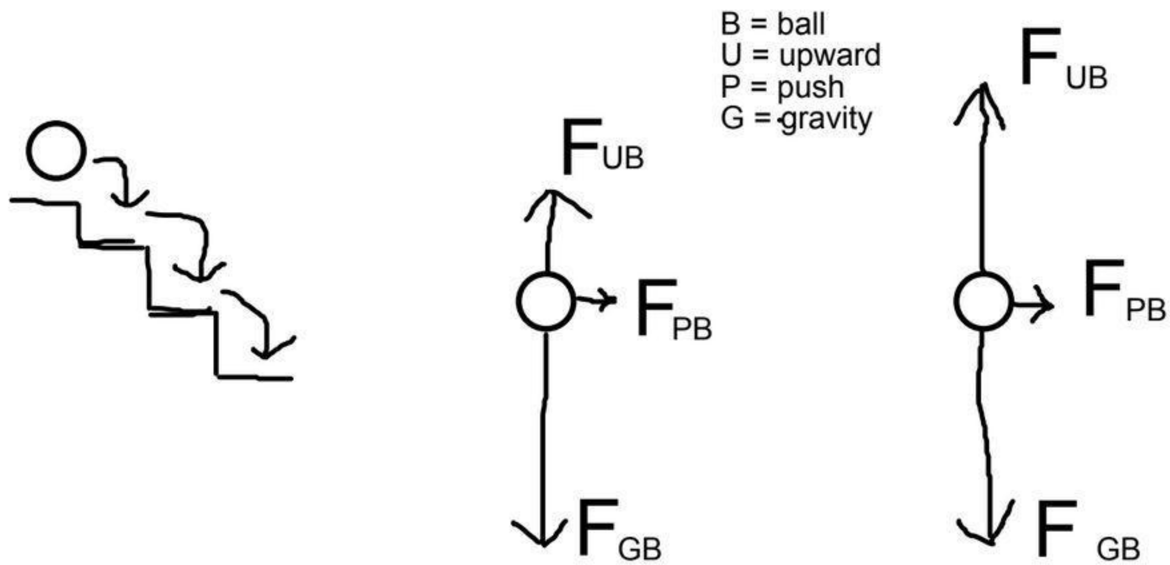


Figure 4.11. A Free-Body Diagram drawn in response to the Ball Falling Down a Stairwell prompt by a student in the Spring 2020 cohort.

As was done with the data from the Spring 2019 cohort, the data from the Spring 2020 cohort were evaluated using the criteria from the Gray Checklist. The results of that evaluation are listed in Table 4.6.

Table 4.6. Criteria fulfilled by the diagrams created by the Spring 2020 cohort in response to the Ball Falling Down a Stairwell prompt.

CRITERION FOR FULFILLMENT	DIAGRAMS FULFILLING CRITERIA (N = 33)
A: Units or Quantity	18 (55%)
B: Consistent Quantity	18 (55%)
C: Movement	1 (3%)
D: Change	22 (67%)
E: Forms	21 (84%)
G: Units Change	0 (0%)
H: Unit Location	0 (0%)
I: Mechanism Shown	0 (0%)
J: System Boundary	0 (0%)

Overall, the diagrams produced by the Spring 2020 cohort illustrated a broader array of criteria from the Gray Checklist, owing to the choice of diagram by many of the students in the cohort. As is shown in Table 4.7, students that chose an Energy Pies or Energy Bars

representation were able to demonstrate several criteria, whether they placed their graphs in conjunction with an Energy Snapshot motif or not. Students who created Energy Trajectory diagrams generally were not able to demonstrate criteria in the Gray Checklist.

Table 4.7. Criteria fulfilled by diagrams created by the Spring 2020 cohort in response to the Ball Falling Down a Stairwell prompt, broken down by type.

DIAGRAM TYPE	CRITERIA FULFILLED
Energy Pies (14 diagrams)	A (Units or Quantity): 14 (100%) B (Consistent Quantity): 14 (100%) D (Change): 14 (100%) E (Forms) 14 (100%)
Energy Bars (4 diagrams)	A (Units or Quantity): 4 (100%) B (Consistent Quantity): 4 (100%) D (Change): 4 (100%) E (Forms): 4 (100%)
Energy Trajectory (10 diagrams)	D (Change): 3 (30%) E (Forms): 1 (10%)
Energy Snapshot (11 diagrams) *Energy Snapshots with Pies: 8 diagrams* *Energy Snapshots with Bars: 1 diagram* *Energy Snapshots with both: 2 diagrams*	A (Units or Quantity): 11 (100%) B (Consistent Quantity): 11 (100%) D (Change): 11 (100%) E (Forms) 11 (100%)
Energy Flow (2 diagrams)	A (Units or Quantity): 2 (100%) B (Consistent Quantity) 2 (100%) D (Change): 2 (100%) E (Forms): 2 (100%)
Free-Body Diagram (1 diagram)	No criteria fulfilled

As a result of choosing energy representations that explicitly made use of both specific forms of energy, explicit quantification of energy through relative size, and changes as shown through an Energy Snapshot scheme, students in the Spring 2020 cohort were able to demonstrate conservation through their diagrams in addition to demonstrating proficient use of multiple forms of energy. The breakdown of the constituent ideas that the Spring 2020 cohort demonstrated through their diagrams is listed in Table 4.8.

Table 4.8. Constituent ideas fulfilled by diagrams created by the Spring 2020 cohort in response to the Ball Falling Down a Stairwell prompt. The requisite criteria for demonstrating each constituent idea are also shown.

CONSTITUENT IDEA	DIAGRAMS FULFILLING CONSTITUENT IDEAS (N = 33)
Conservation (A, B)	18 (55%)
Tracking (A, C, D)	0 (0%)
Forms (E)	21 (64%)
Transformation (A, D, E, G)	0 (0%)
Transfers (A, D, H)	0 (0%)
Mechanism (C, I)	0 (0%)
System (C, J)	0 (0%)

The Spring 2020 cohort demonstrated utility with the Forms constituent idea, although not at the same rate as the Spring 2019 cohort. Also, the Spring 2020 cohort demonstrated conservation through their diagrams at a much higher rate, owing to their use of Energy Bars and Energy Pies with consistent sizing. Also, in general, these diagrams included a sense of narrative and temporality which helped students express the state of the system at different times. This allowed for the expression of change within the system. The narrative structure of an Energy Snapshot diagram is not enough to make the claim that students know energy is being transferred between parts of the system, or to make the claim that students are expressing transformations that are occurring between interactions. However, it is at least enough to show that, out of an arbitrary expression of the total amount of energy in a part of the system, there is a change in how much energy of particular types exist at any given time.

4.2 Energy Diagram #5: Pot of Boiling Water

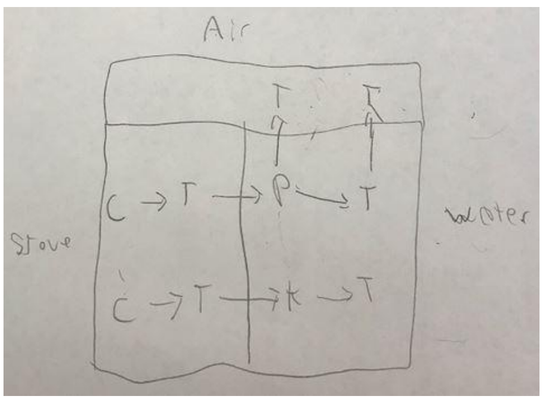
The Energy Diagram #5 prompt, which asks students to draw Energy Tracking Diagrams about a pot of water left to boil on a stove, was assigned to the Spring 2019 cohort on March 19, 2019, and to the Spring 2020 cohort on May 19, 2020. This prompt was assigned to both cohorts in order to move the instruction energy diagramming into a place that did not resemble mechanical energy. The prompt was also the second assignment where students were asked to use Energy Tracking Diagrams specifically. Direct instruction on the "rules" behind Energy Tracking Diagrams were delivered previous to this prompt. Therefore, this prompt can be seen not only as an assessment of the diagrams produced by students in general, and as their ability to navigate a concept that falls outside of the realm of mechanical energy, but also as an assessment of their ability to follow a diagramming scheme laid out by a specific protocol.

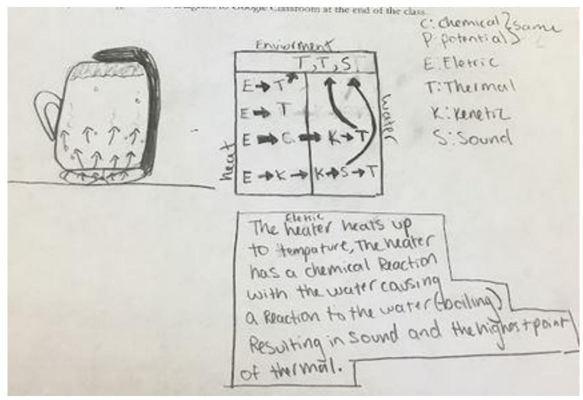
4.2.1 Spring 2019 Cohort Data

Energy Diagram #5 was completed by 19 students in the Spring 2019 cohort. Despite receiving explicit instructions to do so, not all students completed an Energy Tracking Diagram. Two students in the cohort completed Energy Bars diagrams that were arranged in an Energy Snapshot diagram. These diagrams were assessed for fulfillment of criteria in the Gray Checklist, and the results of that evaluation are shown in Table 3.9. Examples of Energy Tracking Diagrams created by this cohort are shown in Figures 3.12 and 3.13.

Table 4.9. Criteria fulfilled by the diagrams created by the Spring 2019 cohort in response to the Pot of Boiling Water prompt.

CRITERION FOR FULFILLMENT	DIAGRAMS FULFILLING CRITERIA (N = 19)
A: Units or Quantity	19 (100%)
B: Consistent Quantity	8 (42%)
C: Movement	17 (89%)
D: Change	17 (89%)
E: Forms	19 (100%)
G: Units Change	17 (89%)
H: Unit Location	16 (84%)
I: Mechanism Shown	4 (21%)
J: System Boundary	15 (79%)





Figures 4.12 and 4.13. Two Energy Tracking Diagrams created by students in the Spring 2019 cohort in response to the Pot of Boiling Water prompt. Both diagrams pictured here are examples of energy branching.

As all students created energy diagrams that followed a protocol requiring adherence to certain constituent ideas (such as quantification of energy units, use of an array of forms, and establishment of a set of system boundaries), a much higher proportion of students fulfilled the Gray Checklist criteria in this prompt. Despite this, few students held to the rule that a consistent quantity be presented in every stage of the diagram, and fewer students indicated a mechanism for the interactions within the diagram. While criteria B and I are requirements of an Energy Tracking Diagram and can be demonstrated through an Energy Bar or Pie setup, these are

requirements that went unfulfilled in several diagrams. The specific criteria fulfilled by students, broken down by type, is listed in Table 4.10.

Table 4.10. Criteria fulfilled by diagrams created by the Spring 2019 cohort in response to the Pot of Boiling Water prompt, broken down by type.

DIAGRAM TYPE	CRITERIA FULFILLED
Energy Tracking Diagram (17 diagrams)	A (Units or Quantity): 17 (100%) B (Consistent Quantity): 8 (47%) C (Movement): 17 (100%) D (Change): 17 (100%) E (Forms): 17 (100%) G (Units Change): 17 (100%) H (Unit Location): 16 (94%) I (Mechanism Shown): 4 (24%) J (System Boundary): 15 (88%)
Energy Tracking Diagrams With Energy Branching (9 diagrams)	A (Units or Quantity): 9 (100%) C (Movement): 9 (100%) D (Change): 9 (100%) E (Forms): 9 (100%) G (Units Change): 9 (100%) H (Unit Location): 9 (100%) I (Mechanism Shown): 3 (33%) J (System Boundary): 9 (100%)
Energy Bars With Energy Snapshots (2 diagrams)	A (Units or Quantity): 2 (100%) E (Forms): 2 (100%)

Due to the high rate of criteria fulfillment for Energy Tracking Diagrams, it follows that a high percentage of these diagrams fulfilled the constituent ideas that served as central learning objectives for the unit. The fulfillment of these constituent ideas by Energy Tracking Diagrams in response to this prompt is shown in Table 4.11; the fulfillment of constituent ideas by the Energy Bars diagrams is not shown in this table.

Table 4.11. Constituent ideas fulfilled by Energy Tracking Diagrams created by the Spring 2019 cohort in response to the Pot of Boiling Water prompt. The requisite criteria for demonstrating each constituent idea are also shown.

CONSTITUENT IDEA	DIAGRAMS FULFILLING CONSTITUENT IDEAS (N = 17)
Conservation (A, B)	8 (47%)
Tracking (A, C, D)	17 (100%)
Forms (E)	17 (100%)
Transformation (A, D, E, G)	17 (100%)
Transfers (A, D, H)	16 (94%)
Mechanism (C, I)	4 (24%)
System (C, J)	15 (88%)

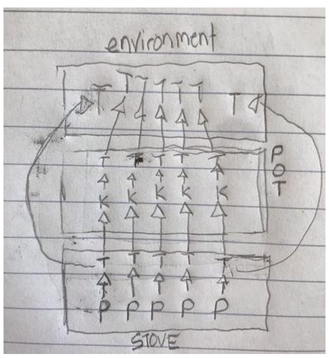
Through their use of the Energy Tracking Diagram scheme, the Spring 2019 cohort demonstrated near universal utility with the tracking, forms, transformation, transfer, and system constituent ideas. However, only eight of the diagrams demonstrated the constituent idea of conservation of energy. All nine of the diagrams that did not demonstrate conservation of energy utilized *energy branching*, described in Section 2.4.3 and identified by Gray, et al. (2019) as a learner-invented diagram.

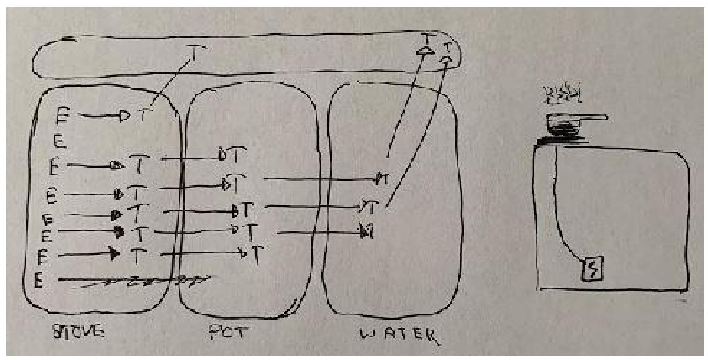
While all Energy Tracking Diagrams demonstrated fulfillment of the Forms constituent idea, the forms shown in the diagrams created by the Spring 2019 cohort are diverse. Students from this cohort made use of seven different forms of energy in order to describe the process of the water boiling in their Energy Tracking Diagrams. The breakdown of the forms used by students in this prompt is given in Table 4.12.

Table 4.12. A breakdown of the variety of energy forms used by the Spring 2019 cohort in diagrams drawn in response to the Pot of Boiling Water prompt.

ENERGY FORM	FREQUENCY OF USE (N = 19)
Chemical	15 (79%)
Thermal	18 (95%)
Potential	11 (58%)
Kinetic	16 (84%)
Sound	4 (21%)
Electric	7 (37%)
Internal	1 (5%)

4.2.2 Spring 2020 Cohort Data





Figures 4.14 and 4.15. Examples of Energy Tracking Diagrams produced by the Spring 2020 cohort in response to the Pot of Boiling Water prompt. Both diagrams contain minor inconsistencies with the Energy Tracking Diagram protocol (such as Energy Branching and an incomplete energy track).

Energy Diagram #5 was completed by 31 students in two class periods in the Spring 2020 cohort. This cohort also received specific prompting to complete Energy Diagram #5 with an Energy Tracking Diagram, an instruction which was followed by all members of the cohort. Despite universal adherence to the format, the cohort displayed irregularities that prevented them from fulfilling all requisite criteria for an Energy Tracking Diagram format. The criteria from the Gray Checklist fulfilled by these diagrams are described in Table 4.13.

Table 4.13. Criteria fulfilled by the diagrams created by the Spring 2020 cohort in response to the Pot of Boiling Water prompt.

CRITERION FOR FULFILLMENT	DIAGRAMS FULFILLING CRITERIA (N = 31)
A: Units or Quantity	31 (100%)
B: Consistent Quantity	27 (87%)
C: Movement	30 (97%)
D: Change	29 (94%)
E: Forms	30 (97%)
G: Units Change	30 (97%)
H: Unit Location	31 (100%)
I: Mechanism Shown	1 (3%)
J: System Boundary	29 (94%)

While the rates of fulfillment of all criteria by the Spring 2020 cohort were high, especially in comparison to the Spring 2019 cohort, students still left the Mechanism Shown criterion unfulfilled, and three students used Energy Branching in their diagrams. These diagrams constituted the bulk of those that did not fulfill the Consistent Units criterion (B). Regardless, fulfillment of constituent ideas remained high. The rate at which the diagrams in this cohort demonstrated constituent ideas is shown in Table 4.14.

Table 4.14. Constituent ideas fulfilled by Energy Tracking Diagrams created by the Spring 2020 cohort in response to the Pot of Boiling Water prompt. The requisite criteria for demonstrating each constituent idea are also shown.

CONSTITUENT IDEA	DIAGRAMS FULFILLING CONSTITUENT IDEAS (N = 31)
Conservation (A, B)	27 (87%)
Tracking (A, C, D)	28 (90%)
Forms (E)	30 (97%)
Transformation (A, D, E, G)	28 (90%)
Transfers (A, D, H)	29 (94%)
Mechanism (C, I)	1 (3%)
System (C, J)	29 (94%)

As with the Spring 2019 cohort, the diagrams of the Spring 2020 cohort indicated near universal utility with several chosen constituent ideas in the Gray Checklist. However, a small

handful of diagrams left certain criteria unfulfilled on occasion. In particular, three diagrams that did not fulfill the conservation of energy constituent idea used Energy Branching to indicate divergences in an energy track, as was also seen in the Spring 2019 cohort.

Also in keeping with the diagrams of the Spring 2019 cohort, the diagrams produced by the Spring 2020 cohort made use of several different forms of energy within the diagram. While students almost unilaterally used thermal energy in their diagram in some way, and many made use of kinetic and potential energy, no students used sound and internal energy, marking a shift from the Spring 2019 cohort. The breakdown of how students used different forms of energy in the Spring 2020 cohort is given in Table 4.15.

Table 4.15. A breakdown of the variety of energy forms used by the Spring 2020 cohort in diagrams drawn in response to the Pot of Boiling Water prompt.

ENERGY FORM	FREQUENCY OF USE (N = 31)
Chemical	4 (13%)
Thermal	30 (97%)
Potential	14 (45%)
Kinetic	19 (61%)
Electric	8 (26%)

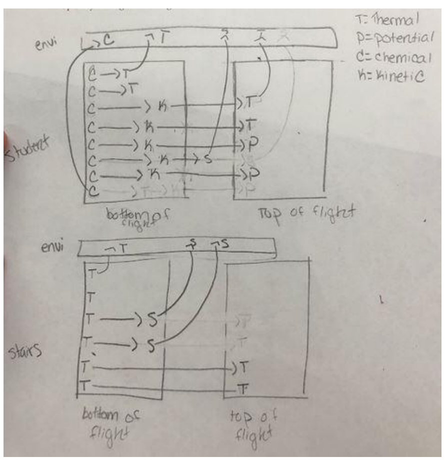
4.3 Energy Diagram #9: Student Running Up Stairs

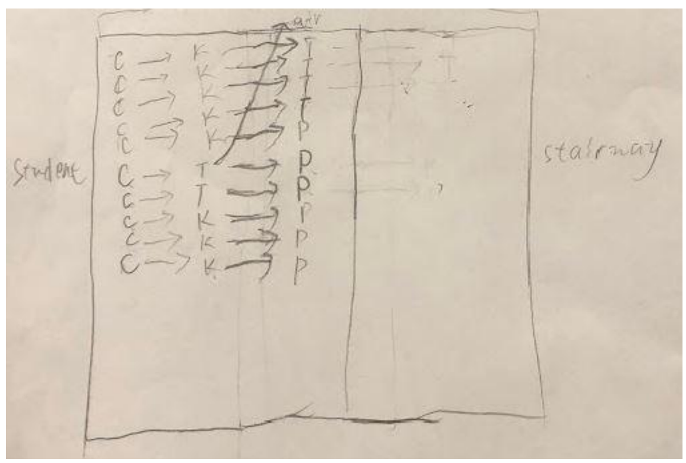
Energy Diagram #9, which asked students to draw an energy diagram to represent the scenario of a student running up a set of stairs, was assigned to the Spring 2019 cohort on March 29, 2019, and to the Spring 2020 cohort on June 5, 2020. On account of the different timing for the delivery of this prompt between 2019 and 2020, the assignment served as a terminal diagram prompt for the Spring 2020 cohort, but was not a terminal assignment for the Spring 2019 cohort. The Spring 2019 cohort was asked to draw Energy Tracking Diagrams for this assignment, whereas the Spring 2020 cohort was asked to draw whatever diagrams came to mind. Students in

the Spring 2019 cohort were also asked to come up with a written definition for energy in groups of three on April 10, 2019.

4.3.1 Spring 2019 Cohort Data

Energy Diagram #9 was completed by 16 students in the Spring 2019 cohort. The Gray Checklist criteria fulfilled by these diagrams shows striking resemblance to the criteria fulfilled by the diagrams drawn in response to the Pot of Boiling Water prompt. The criteria fulfilled by these diagrams is shown in Table 4.16.





Figures 4.16 and 4.17. Two examples of Energy Tracking Diagrams drawn by the Spring 2019 cohort in response to the Student Running Up Stairs prompt. Figure 3.16 is a dual diagram setup, showing separate energy tracks for the student and the stairs. Figure 3.17 is an Energy Tracking Diagram where the student indicates no energy transfers from the student to the stairs, despite defining the stairs as part of the system.

Table 4.16. Criteria fulfilled by the diagrams created by the Spring 2020 cohort in response to the Student Running Up Stairs prompt.

CRITERION FOR FULFILLMENT	DIAGRAMS FULFILLING CRITERIA (N = 16)
A: Units or Quantity	16 (100%)
B: Consistent Quantity	12 (75%)
C: Movement	15 (94%)
D: Change	16 (100%)
E: Forms	16 (100%)
G: Units Change	16 (100%)
H: Unit Location	16 (100%)
I: Mechanism Shown	0 (0%)
J: System Boundary	16 (100%)

While the diagrams produced by this cohort demonstrated several criteria across the board, there were a handful of diagrams that did not fulfill the consistent quantity or movement criteria, as was the case with responses to the Pot of Boiling Water prompt. Furthermore, this cohort did not express the mechanism for changes at all, leaving the Mechanism Shown criteria completely unfulfilled. Regardless, this cohort drew diagrams that fulfilled constituent ideas in the Gray Checklist at a high rate. The breakdown of the fulfillment of constituent ideas by the Spring 2019 cohort on this prompt is shown in Table 4.17.

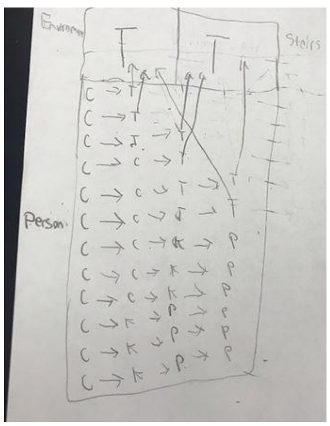
Table 4.17. Constituent ideas fulfilled by Energy Tracking Diagrams created by the Spring 2019 cohort in response to the Student Running Up Stairs prompt. The requisite criteria for demonstrating each constituent idea are also shown.

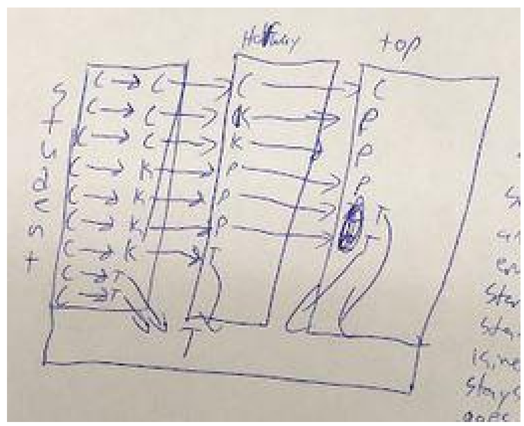
CONSTITUENT IDEA	DIAGRAMS FULFILLING CONSTITUENT IDEAS (N = 16)
Conservation (A, B)	12 (75%)
Tracking (A, C, D)	15 (94%)
Forms (E)	16 (100%)
Transformation (A, D, E, G)	16 (100%)
Transfers (A, D, H)	16 (100%)
System (C, J)	15 (94%)

The Spring 2019 cohort drew Energy Tracking Diagrams universally, as prompted to do so. However, several diagrams deviated from the protocol for drawing the diagrams, specifically

in regard to drawing energy tracks throughout the diagram, and through attempts to build a temporal narrative into the diagrams.

One student in this cohort used Energy Branching in their diagram. Two students used a new tracking scheme, where units of energy come together as they move from one part of the diagram to another. This tendency was coded as *Energy Grouping* during the analysis of the diagrams. One of these diagrams showed the unit that “received” a previous group of units increasing in size; this tendency was coded *Energy Scaling* during the analysis of the diagrams. All of these examples register in the checklist data as not fulfilling Criterion B, which indicates that a consistent number of units occur along each phase of the diagram.

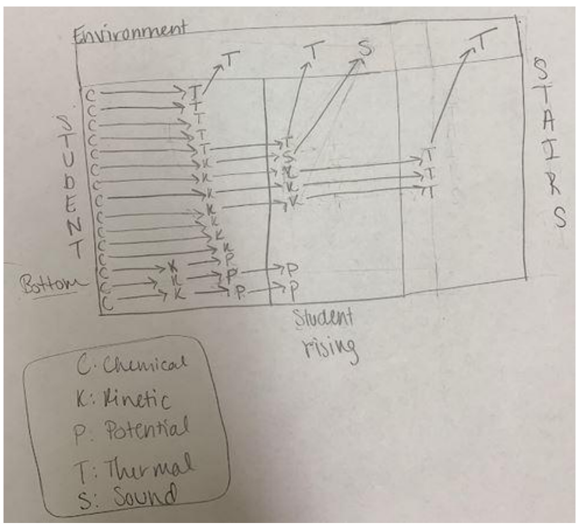


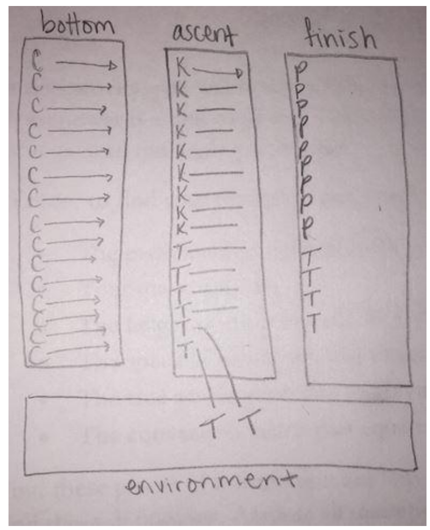


Figures 4.18 and 4.19. Two Energy Tracking Diagrams that demonstrate the Energy Grouping idea. The diagram on the left demonstrates the Energy Scaling idea. The diagram on the right demonstrates the Energy Snapshot idea within a single Energy Tracking Diagram.

In addition to these new structures that alter the way energy is tracked through student-defined systems, students drew diagrams that added temporal, narrative structure throughout the diagram, much like the Energy Snapshots drawn in response to the Ball Falling Down the Stairs prompt. Nearly the entire cohort (15 of 16 students) made attempts to place a timeline through their Energy Tracking Diagram, usually by dividing the task of running up the stairs into three distinct parts: a stage where the student is at rest at the bottom of the stairs, a

stage where the student is running up the stairs, and a stage where the student is at the top of the stairs and has concluded their run. The manner in which students include these temporal narratives differ; some students chose to draw separate Energy Tracking Diagrams for each phase, while others attempted to indicate sections of a single diagram that represented each part of the motion.





Figures 4.20 and 4.21. Energy Tracking Diagrams produced by the Spring 2019 cohort in response to the Student Running Up Stairs prompt, which feature attempts at a temporal narrative structure for the activity. In these diagrams, the creators of the diagrams divide the narrative into locations and student action; these diagrams are effectively Energy Snapshots which use the position of the student as the narrative dimension.

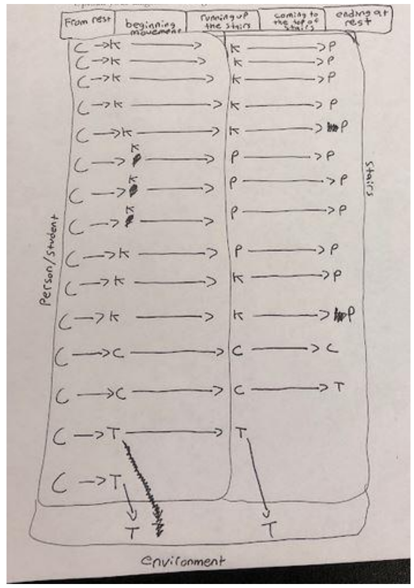


Figure 4.22. An Energy Tracking Diagram produced by a student in the Spring 2019 cohort in response to the Student Running Up Stairs prompt. This diagram uses a timeline overlay to indicate which sections of the diagram correspond to certain parts of the temporal narrative.

While the Student Running Up Stairs prompt is a pedagogical return to mechanical energy, students still made use of a somewhat diverse array of energy forms to draw their diagrams, just as they did in response to the Pot of Boiling Water prompt. The energy forms used by students to complete their Energy Tracking Diagrams during this assignment are shown in Table 4.18.

Table 4.18. A breakdown of the variety of energy forms used by the Spring 2019 cohort in diagrams drawn in response to the Student Running Up Stairs prompt.

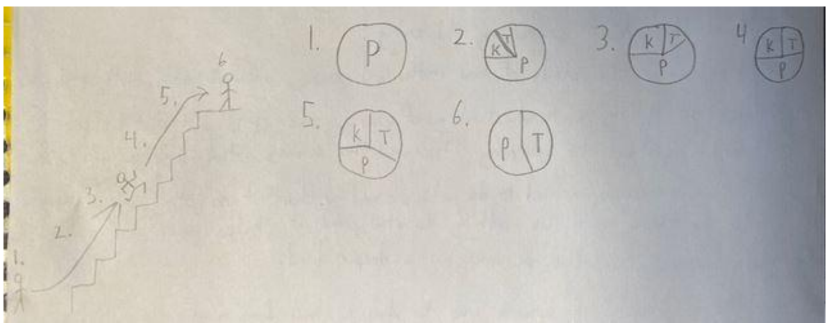
ENERGY FORM	FREQUENCY OF USE (N = 16)
Chemical	16 (100%)
Thermal	16 (100%)
Potential	16 (100%)
Kinetic	16 (100%)
Sound	1 (6%)

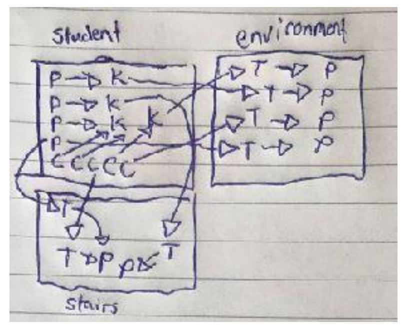
With the lone exception of a student who included sound energy in their diagram, every student made use of not only kinetic and potential energy (forms of energy which were part of

the calculations involved in the Find Your Horsepower assignment), but also thermal and chemical energy, in order to complete their diagrams.

4.3.2 Spring 2020 Cohort Data

Energy Diagram #9 was completed by 33 students in the Spring 2020 cohort. The delivery of the Student Running Up Stairs prompt to this cohort differed significantly from that of the Spring 2019 cohort. The prompt was the final assignment of the 2020 school year.





Figures 4.23 and 4.24. Diagrams created by students in the Spring 2020 cohort in response to the Student Running Up Stairs prompt.

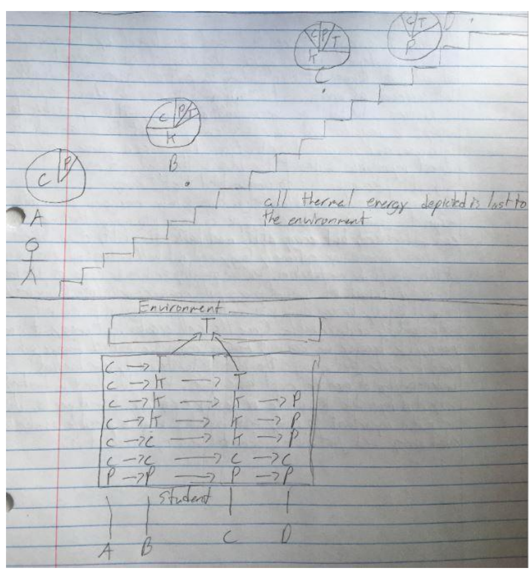


Figure 4.25. A dual diagram created by a student in the Spring 2020 cohort in response to the Student Running Up Stairs prompt. This diagram also uses the Energy Grouping and Energy Snapshot ideas within a single Energy Tracking Diagram.

As a result of the lack of constraints on the diagram format, student diagrams varied. The breakdown of the different diagram formats students used is given in Table 4.19.

Table 4.19. A breakdown of the types of energy diagrams produced by the Spring 2019 cohort in response to the Student Running Up Stairs prompt. As a few students drew more than one diagram, the percentages do not add to 100%.

DIAGRAM TYPE	NUMBER OF DIAGRAMS (N = 33)
Energy Tracking Diagrams	18 (55%) *3 of 18 demonstrate Energy Branching*
Energy Snapshots	13 (36%)
Energy Pies	9 (27%) *all 9 are Energy Snapshot diagrams*
Energy Bars	5 (18%) *4 of 5 are Energy Snapshot diagrams*
Energy Flow Diagram	1 (3%)
Energy Trajectory	1 (3%)
Learner-invented Diagram	1 (3%)

Energy Tracking Diagrams made up the majority of the diagrams in the Spring 2020, but students drawing these diagrams did not use them with an Energy Snapshot scheme. Those who drew Energy Pies or Energy Bars diagrams, however, did employ Energy Snapshot schemes almost entirely, with only one of these diagrams containing no link to an event in time. Three students created diagrams using other formats used for Energy Diagram #1. The Gray Checklist criteria that each of these diagrams met is shown in Table 4.20, and the criteria broken down by type of diagram is shown in Table 4.21.

Table 4.20. Criteria fulfilled by the diagrams created by the Spring 2020 cohort in response to the Students Running Up Stairs prompt.

CRITERION FOR FULFILLMENT	DIAGRAMS FULFILLING CRITERIA (N = 33)
A: Units or Quantity	33 (100%)
B: Consistent Quantity	24 (72%)
C: Movement	20 (60%)
D: Change	21 (64%)
E: Forms	33 (100%)
G: Units Change	19 (58%)
H: Unit Location	17 (52%)
J: System Boundary	19 (58%)

Table 4.21. Criteria fulfilled by diagrams created by the Spring 2020 cohort in response to the Student Running Up Stairs prompt, broken down by type.

DIAGRAM TYPE	CRITERIA FULFILLED
Energy Tracking Diagram (18 diagrams)	A (Units or Quantity): 18 (100%) B (Consistent Quantity): 13 (72%) C (Movement): 18 (100%) D (Change): 18 (100%) E (Forms): 18 (100%) G (Units Change): 18 (100%) H (Unit Location): 17 (94%) J (System Boundary): 17 (94%)
Energy Pies (9 diagrams, all Energy Snapshots)	A (Units or Quantity): 9 (100%) B (Consistent Quantity): 9 (100%) C (Movement): 2 (22%) D (Change): 2 (22%) E (Forms): 9 (100%)
ENERGY BARS (5 diagrams, 4 of 5 are Energy Snapshots)	A (Units or Quantity): 5 (100%) B (Consistent Quantity): 2 (40%) E (Forms): 5 (100%)
ENERGY FLOW DIAGRAM (1 diagram)	A, B, D, E
ENERGY TRAJECTORY (1 diagram)	A, B, E
LEARNER-INVENTED “ENERGY PLOT” (1 diagram)	A, B, E

The rates of constituent idea fulfillment in the Spring 2020 cohort for Energy Diagram #9 are split along diagram types. In general, Energy Tracking Diagrams are able to fulfill more of these ideas than Energy Bar and Pie representations. These rates are listed in Table 4.22.

Table 4.22. Constituent ideas fulfilled by Energy Tracking Diagrams created by the Spring 2019 cohort in response to the Student Running Up Stairs prompt. The requisite criteria for demonstrating each constituent idea are also shown.

CONSTITUENT IDEA	DIAGRAMS FULFILLING CONSTITUENT IDEAS (N = 16)
Conservation (A, B)	24 (72%)
Tracking (A, C, D)	20 (61%)
Forms (E)	33 (100%)
Transformation (A, D, E, G)	18 (55%)
Transfers (A, D, H)	17 (51%)
System (C, J)	19 (58%)

As is the case with the Spring 2019 cohort, the Spring 2020 cohort used a variety of different forms of energy in their diagrams, regardless of whether they used Energy Tracking Diagrams, Energy Bars or Pies, or a different diagram. The forms of energy that students in the Spring 2020 cohort used in their diagrams are listed in Table 4.23.

Table 4.23. A breakdown of the variety of energy forms used by the Spring 2020 cohort in diagrams drawn in response to the Student Running Up Stairs prompt.

ENERGY FORM	FREQUENCY OF USE (N = 33)
Chemical	9 (27%)
Thermal	23 (70%)
Potential	32 (97%)
Kinetic	33 (100%)

Like the Spring 2019 cohort, the Spring 2020 cohort made use of potential and kinetic energy in a nearly universal manner in their diagrams, regardless of the type of diagram. This is in keeping with the nature of the prompt, which is focused largely on mechanical forms of energy. Yet, fewer students employed chemical and thermal energy in their interactions than the Spring 2019 cohort.

In Chapter 5, these results are used to describe how the energy diagram data indicate answers to the research questions given in Chapter 2. These data can speak to the ability of the

Gray Checklist to detect trends in the set of diagrams as a whole, and whether any trends that go undetected warrant the addition of criteria or constituent ideas. Furthermore, these data can help determine whether the checklist should be modified, either in content or in use, to accommodate shifts in instructional modality.

CHAPTER 5

DISCUSSION OF RESULTS

The primary use of the Gray Checklist is to show the alignment of an energy diagram (or a set of energy diagrams) to the model of energy outlined in the NGSS. The results of such an analysis are given in this chapter, broken down by sections into the research questions outlined in Chapter 1. Section 5.1 addresses the question of whether the Gray Checklist is capable of detecting trends in the energy diagrams produced by high school students as part of a college-preparatory curriculum. Section 5.2 addresses proposed changes to the Gray Checklist based on trends in the data it left undetected. Section 5.3 addresses whether or not there is a difference between cohorts that were engaging in the material, and working with energy diagramming schemes, in a different mode of instruction than previous classes.

5.1 Use of the Gray Checklist to Detect Trends in Student-Produced Diagrams

A focus of this thesis is to show how the Gray Checklist can account for the trends that high school students present in the production of energy diagrams during a college-preparatory high school physics class. As is illustrated in Figures 5.1 and 5.2, the Gray Checklist is able to detect whether or not diagrams meet particular constituent ideas identified as important in this particular curriculum to the extent that students fulfill them.

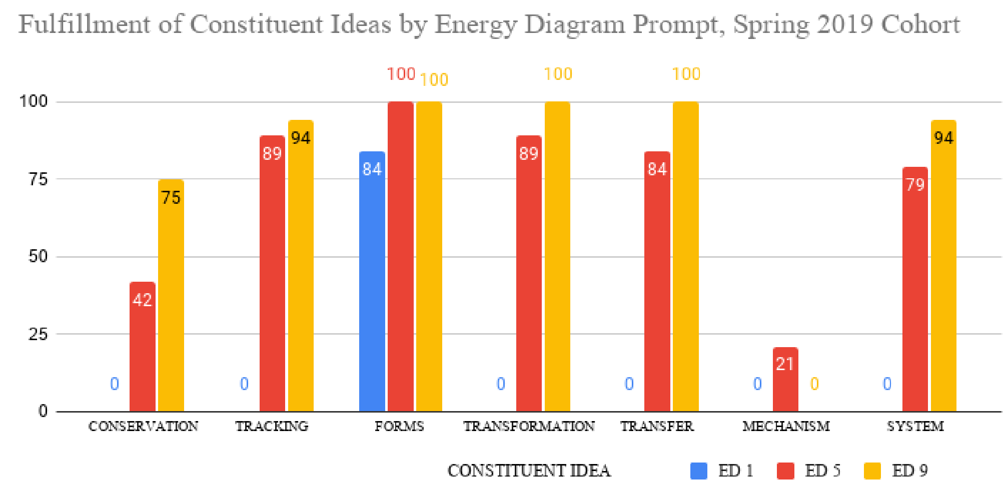


Figure 5.1. A graph comparing the percentage of constituent ideas demonstrated by the energy diagrams of the Spring 2019 cohort in each of the three energy diagram prompts.

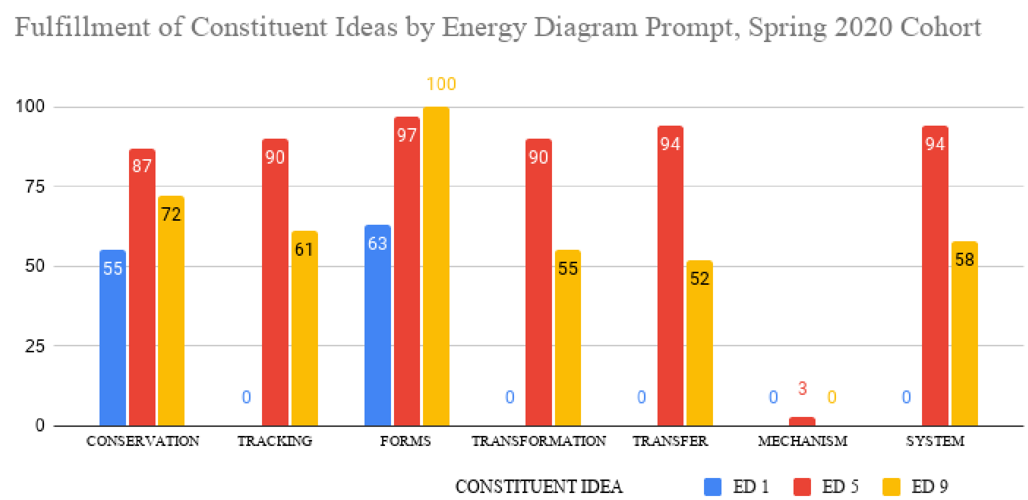


Figure 5.2. A graph comparing the percentage of constituent ideas demonstrated by the energy diagrams of the Spring 2020 cohort in each of the three energy diagram prompts.

In cases where Energy Tracking Diagrams were mandated for use, such as in Energy Diagram 5 and Energy Diagram 9 for the Spring 2019 cohort, and Energy Diagram 5 in the Spring 2020 cohort, fulfillment of the identified constituent ideas is high. The only constituent idea that remained largely unfulfilled by students was that of Mechanism, owing largely to the

omission of color-coded arrows in many of the Energy Tracking Diagrams completed. Most constituent ideas are fulfilled at a high rate because Energy Tracking Diagrams lay out a clear protocol and set of rules for how students should draw the diagram. According to the protocol and rules for Energy Tracking Diagrams laid out by Scherr, et al. (2012), students are expected to express conservation of energy by keeping the number of units in the diagram consistent, to show energy units moving from one object to another (transfer) and changing forms (transformation), to establish energy tracks along which the distinct ways energy moves through the system can be accounted for, and to use forms of energy they feel best fit the situation at hand. Finally, students do this inside an established system, and are expected to demonstrate that some mechanism makes transfers and transformations of energy possible.

Regardless of these requirements, some students were able to draw Energy Tracking Diagrams that do not fulfill these expectations in the protocol and rules laid out by Scherr, et al. (2012); these deviations from the requirements of an Energy Tracking Diagram register in the data as criteria unfulfilled. In particular, the trends of Energy Branching, Energy Grouping, Energy Scaling, and Energy Snapshots, due to the nature of the diagramming schemes in which they are seen, illustrate this idea with high frequency.

The use of Energy Branching, Energy Grouping, and Energy Scaling to express a junction in an energy track registers as a diagram leaving criterion B (Consistent Number of Units) unfulfilled, and therefore not fulfilling the Conservation constituent idea. It may be the case that students require a different mechanism through which to express a divergence or a convergence in an energy track, and therefore find that the restriction of keeping the same number of units through each stage of the diagram prevents that expression, instead requiring them to draw more energy tracks than they feel is necessary. Drawing energy units of different

sizes or creating junctions in already established energy tracks allow students to express a particular path for energy throughout the system using a smaller number of symbols than an Energy Tracking Diagram might otherwise require.

Another example of a trend seen in the data which would instead register as an unfulfilled checklist criterion is the use of Energy Bar and Energy Pie schemes to express how energy in different forms changes in a particular situation with regard to time. Because Energy Bars and Energy Pies express quantities of energy as relative areas rather than units which can be tracked and moved within a system, these diagrams frequently do not fulfill the criteria required to demonstrate the Transfer, Transformation, or Tracking constituent ideas. This is shown in the criteria fulfillment data for Energy Diagram #1 in the Spring 2020 cohort: all of the Energy Bars and Energy Pies diagrams needed to use a template of time in order to make useful snapshots, and therefore no diagram that was coded as an Energy Snapshot registered another code that might indicate such a practice. In two specific instances, students coupled their Energy Bar or Pie diagram schemes with an accompanying Energy Tracking Diagram, in order to express how discrete units of energy within a track can match up to the broad quantities expressed in the Energy Bar or Pie scheme. An example of this dual diagram tendency is shown in Figure 4.25.

The Gray Checklist aids its assessor in determining whether or not students make use of identifiable forms of energy. According to the checklist, the use of different forms of energy in a diagram is both a criterion to meet and a constituent idea that a diagram fulfills. However, the checklist does not go beyond meeting that simple requirement. As a result, that single criterion lumps into one category the diverse ways in which students used different forms of energy to express the behavior of a system in terms of energy. In Energy Diagram #5, both the Spring 2019 and the Spring 2020 cohorts used a variety of forms of energy to explain how the water on the

stove boils away. It was not uncommon for students to use several different forms of energy within the same diagram to express the forms of energy that water in a pot on the stove might have as it is ultimately brought to a boil. The same can be said for Energy Diagram #9: students made use of at least three types of energy to complete the diagram, using chemical energy to the extent that they wanted to express how the chemical energy of the person running up the stairs was "spent."

Finally, the Gray Checklist does not detect the trend demonstrated by each cohort in both the Energy Bar/Pie diagrams and Energy Tracking Diagrams in Energy Diagram #9, where students divide the diagrams into subsections that correspond to temporal or positional landmarks for the behavior (like the height of the runner in relation to the flight of stairs or the relative time elapsed after the motion starts). Students created these subdivisions within the Energy Tracking Diagram without subverting or breaking other rules: each Energy Tracking Diagram with these subdivisions still maintained coherent energy tracks throughout the diagram, and no energy track led to energy leaving the system, thus ensuring conservation of energy.

5.2 Suggested Checklist Modifications: Addition of Energy State and Narrative Dimension

As the Gray Checklist is founded upon the metaphors inherent to the NGSS and is an attempt to use the NGSS model for energy as a tool for assessment of energy diagrams, any modifications to the Gray Checklist should also have their roots in the language of the NGSS. However, the use of the Gray Checklist in this particular application exposes a design flaw in the NGSS itself: the idea of energy, and of using energy to represent and predict the course of an interaction between objects in a system, is itself a modeling exercise, which is not fully addressed in the Matter and Energy Crosscutting Concept. The results from these cohorts suggest the addition of two criteria for fulfillment and the addition of one constituent idea, which helps to

bring the Gray Checklist into alignment with two other Crosscutting Concepts in the NGSS: Stability and Change, and Systems and System Modeling.

5.2.1 Energy State as a Constituent Idea

In the Energy Snapshot diagrams and the subdivided Energy Tracking Diagrams, students implement their own organizational schemes to track energy units at all times throughout the behavior of a system. This is in keeping with the analogy for energy that Feynman, et al. (1963) used to describe energy in the Feynman lecture on Conservation of Energy: Feynman likens energy to blocks in Dennis the Menace's room. Conservation of energy dictates that Dennis has the same number of blocks at *any given time*, and that the counting of those blocks is regardless of their location, or who brought other blocks with them when visiting Dennis.

This idea, that the total energy of a system can be tracked and should be the same at any given time for a particular system, is best described as the system's *energy state:* a simple measurement of how much energy a system might have, with an expression of how it is distributed among objects in the system. The difference between the two formats with regard to energy state is simply whether or not the diagramming scheme is inherently built for such an expression. In a series of Energy Bars or Energy Pies, the student may make any number of Bars or Pies, as long as they accompany the physical state of the system; in fact, the fulfillment of the Energy State constituent idea *makes* a series of Energy Bars or Energy Pies an energy diagram with utility. In an Energy Tracking Diagram, the tendency to subdivide a box that represents an object into spaces that coincide with its presence in time or its position in space is possibly a stretch of the rules, if not a broken one.

The Energy State constituent idea is rooted in the NGSS Crosscutting Concepts, but not in Energy and Matter. Rather, the idea of tracking changes over time is more closely aligned with the Stability and Change Crosscutting Concept, which alludes to the importance of tracking changes in any system over time as a means for understanding it. Rather than simply thinking about the energy within a system, students are using energy diagrams as a means to make sense of changes in a system, with graphical representations of energy as the lens through which that examination happens.

Furthermore, the Energy State constituent idea aligns with the Systems and System Models Crosscutting Concept. Students are using energy diagrams as models of change within the system, and their models exchange elements of the energy metaphor for others. In this particular case, some diagrams in this study account for energy at certain times or certain positions, like Dennis the Menace fumbling for all 28 of his blocks in Feynman's analogy. In particular, some Energy Tracking Diagrams are adapted from the original protocol to include a place where every energy track is accounted for, usually resulting in the same number of stops in each track.

5.2.2 Criteria for Fulfillment of the Energy State Constituent Idea

To wit, the Constituent Idea of *Energy State* contains two parts. Students must track all quantities of energy across the system throughout their diagrams, and organize their energy tracks using a single chosen dimension, such as time or position. It is this template for tracking that students use to demonstrate conservation of energy within the system.

In order to meet the Energy State Constituent Idea, two criteria for fulfillment from Table 3.2 must be met. First, the diagram must include explicit quantities or units of energy for

students to track, fulfilling the Units or Quantity criterion. In addition to this criterion, a fourteenth criterion for fulfillment must be included in this part of the Gray Checklist: that of *Narrative Dimension*. This criterion would stipulate that the student has indicated a particular dimension through which their tracking narrative has been scaffolded. That narrative dimension can be the time over which a system exhibits a particular behavior, or the position of an object in a system. In either case, the diagram should use the Narrative Dimension as a means to organize the tracking of quantities or units throughout the system over the course of a diagram.

It is noteworthy that an energy diagram does not necessarily have to meet any other criteria in the Gray Checklist in order to demonstrate a sense of state. Just as the Dennis the Menace analogy from Feynman might treat energy as amorphous blocks, and just as Nordine, et al. (2019) argues that energy moves in a single amorphous form from one object to another, a diagram might only track a single quantity of energy for a single object and still fulfill the Energy State constituent idea. However, for many diagrams drawn by students, such an abstraction is unlikely and unworkable. Nearly all students in both cohorts maintained the use of different forms of energy throughout the energy unit, and showed energy tracks, transformations, and transfers in their diagrams. This is an indication that students not only need to express the Energy State of the system in their diagrams, but also need to use energy forms, tracks, transfers, and transformations as further ways to organize their diagrams.

5.3 The Gray Checklist and Changes in Modality

Finally, this thesis means to address how the Gray Checklist might have been affected in its reliability with a change in modality. The abrupt switch from in-person to remote instruction in light of the COVID-19 pandemic allowed the checklist to be tested in different instructional environments while evaluating the same types of diagrams. For this purpose, the interrater

reliability measure presented by Gray, et al. (2019) for the Gray Checklist is used in order to make a direct comparison between the same types of diagrams in these different cohorts. If differences occur that fall outside of the interrater reliability range without explanation, then changes in the checklist due to a modality shift may be necessary. An analogue to this treatment of the data is that of affixing an error bar to any particular measurement of criteria fulfillment. Any comparison of checklist criteria that falls within the interrater reliability range indicates the curriculum worked in an equivalent manner from cohort to cohort. Any comparison that falls outside of this interrater reliability range warrants can either be directly explained through previously stated trends, or through a modality shift.

A comparison of the outcomes of Energy Diagram #5 and Energy Diagram #9 for the Spring 2019 cohort and the Spring 2020 cohort can show whether the shift in modality affected the utility of the Gray Checklist. For this comparison, the rates at which Energy Tracking Diagrams in both cohorts fulfilled the same criteria in the Gray Checklist was compared. Then, these rates were compared against the interrater reliability range given by Gray, et al. for their checklist (a factor of 0.88, or 88%). Therefore, the comparison of each criteria should match to within a factor of 0.12 (12%) in order to show equivalent outcomes.

5.3.1 Comparison of Energy Diagram #5 Between Cohorts

In response to the Pot of Boiling Water prompt, shown in Table 4.23, nearly all rates of criteria fulfillment fell within the interrater reliability range derived from the original interrater reliability rate of the Gray Checklist. The only criterion that differed outside of that range was the Consistent Units or Quantity criterion. This difference is due to the large number of diagrams in which Energy Branching, Energy Scaling, or Energy Grouping appeared, a tendency which would not otherwise be detected by the checklist. The difference in fulfillment of criterion I, the

Mechanism Shown criterion, is much higher than other criteria which fell between the interrater reliability range. This difference is due to the absence of any mechanism shown in these diagrams, particularly a color-coded arrow which would indicate the mechanism.

Table 5.1. Rates of fulfillment of Gray Checklist criteria between students in the Spring 2019 and Spring 2020 cohorts that completed Energy Tracking Diagrams to answer the Pot of Boiling Water prompt.

CRITERION	SPRING 2019 FULFILLMENT (n = 17)	SPRING 2020 FULFILLMENT (n = 31)	DIFFERENCE IN PERCENTAGE
A	100% (17)	100% (31)	0%
B	47% (8)	87% (27)	40%
C	100% (17)	97% (30)	3%
D	100% (17)	94% (29)	6%
E	100% (17)	97% (30)	3%
G	100% (17)	97% (30)	3%
H	94% (16)	100% (31)	6%
I	24% (4)	3% (1)	21%
J	88% (15)	94% (29)	6%

5.3.2 Comparison of Energy Diagram #9 Between Cohorts

In response to the Student Running Up Stairs prompt, students completing Energy Tracking Diagrams in both cohorts exhibited nearly identical rates of fulfillment of Gray Checklist criteria, falling well within the interrater reliability range.

Table 5.2. Rates of fulfillment of Gray Checklist criteria between students in the Spring 2019 and Spring 2020 cohorts that completed Energy Tracking Diagrams to answer the Student Running Up Stairs prompt.

CRITERION	SPRING 2019 FULFILLMENT (n = 16)	SPRING 2020 FULFILLMENT (n = 18)	DIFFERENCE IN PERCENTAGE
A	100% (16)	100% (18)	0%
B	75% (12)	72% (13)	3%
C	94% (15)	100% (18)	6%
D	100% (16)	100% (18)	0%
E	100% (16)	100% (18)	0%
G	100% (16)	100% (18)	0%
H	100% (16)	94% (17)	6%
I	0% (0)	0% (0)	0%
J	100% (16)	94% (17)	6%

5.3.3 Effect from Modality Shift

As a diagramming scheme, Energy Tracking Diagrams are stable and regimented. Both cohorts were given variations on the same instruction with regard to this diagramming scheme, and both cohorts exhibited almost all of the same tendencies with regard to their completion. This comparison shows that the Gray Checklist was not able to detect any shifts in their completion due to the modality alone; shifts in their completion are explained by trends in the diagrams themselves. The differences between initial diagrams in the Spring 2019 cohort and the diagrams that came at the end of the Spring 2019 and Spring 2020 cohorts involved trends in diagram execution, such as the omission of the mechanism through which an interaction occurs (a color-coded arrow), or through the adaptation of the Energy Tracking Diagram format to fit the Energy Snapshot paradigm. These are differences not necessarily detected by the checklist, and were made by students regardless of the modality.

CHAPTER 6

CONCLUSION

The Gray Checklist was formulated as a tool for assessing energy diagrams created by students in the course of learning about energy, which relies heavily on metaphorical language and conceptual thinking. This checklist draws upon the diverse landscape of metaphors that are used to express energy in the Next Generation Science Standards, and works those metaphors into an assessment tool that can be easily used, and its results easily interpreted. This thesis seeks to identify improvements to the Gray Checklist that can be made, and in some cases, alternative uses for the Gray Checklist that might aid the type of teacher that Gray, et al. (2019) describe in their investigation: teachers who struggle with teaching energy on its own, let alone the use of diagramming schemes to that end. Another goal of this thesis is to establish whether or not those improvements must be implemented in response to shifts in modality.

6.1 On the Use of the Gray Checklist to Assess Energy Diagram Trends

The Gray Checklist demonstrated effectiveness in detecting some of the trends of the energy diagrams drawn by this particular group of students. The data from the use of the Gray Checklist in evaluating the energy diagrams from three different prompts across two cohorts show the ability to detect the fulfillment of seven identified constituent ideas and their requisite criteria for fulfillment. In this way, the Gray Checklist is a useful tool for evaluating student energy diagrams.

Despite its effectiveness in detecting certain trends in the energy diagrams, the Gray Checklist misses others. The tendencies of Energy Grouping, Energy Scaling, and Energy Branching go undetected by the Gray Checklist, instead registering as an inability to show a

consistent number of units within energy tracks in the diagram, and therefore a lack of demonstration of conservation of energy, a central constituent idea of the Gray Checklist and a fundamental idea to energy as a whole. However, the Gray Checklist is not designed to allow the assessor to make a judgment about whether or not a student *understands* conservation of energy when this constituent idea goes unfulfilled. Furthermore, the Gray Checklist does not account for the possibility that a student may be breaking the conventions specified by a particular diagramming scheme regarding what conservation of energy *should* or *must* look like in order to achieve a particular purpose.

The Gray Checklist also does not adequately detect the trend demonstrated in several Energy Snapshot diagrams involving Energy Bar and Energy Pie depictions, and in several Energy Tracking Diagrams that were subdivided along temporal or spatial dimensions. In several cases, students relied on a narrative structure to organize quantities of different types of energy, and even invented their own conventions within their chosen diagramming scheme in order to accommodate such a description. This trend did not show in the data as the fulfillment, or lack of fulfillment, of any particular Gray Checklist criteria, nor did it compromise the ability of diagrams to fulfill its constituent ideas.

Finally, the Gray Checklist is able to detect the use of different forms of energy in energy diagrams, but does not account for the diversity of the forms used in certain diagram prompts. While students drew from a predictable array of energy forms in their diagrams, their use varied greatly. In particular, student use of different forms of energy in the Pot of Boiling Water prompt varied greatly, most likely in response to the vague nature of the forms of energy with regard to thermodynamics. The Gray Checklist can indeed detect that a student can make use of different forms of energy in order to construct an explanation, but it cannot effectively explain why

students might choose to express the energy that is contained in water as a consequence of its internal temperature as *potential*, *chemical*, *kinetic*, *thermal*, or some other form. Section 6.4.2 discusses further how such judgments made by an instructor or an evaluator could be written as performance indicators that run parallel to the constituent ideas in the Gray Checklist.

6.2. On Suggested Modifications to the Gray Checklist

The addition of a single constituent idea, Energy State, is a necessary addition to the Gray Checklist. This constituent idea can apply to a whole system (which was demonstrated in modified Energy Tracking Diagrams) or in individual objects (as shown in Energy Bar or Energy Pie arrangements). While the NGSS states in Standard HS-PS-3-1 that this sort of model must be computational, relying on measurable quantities and formulae in order to be useful, diagramming schemes like Energy Tracking Diagrams and Energy Bar or Energy Pie schemes can prove effective at tracking the state of a system when a narrative dimension (such as time or position) are involved. Showing the system at particular times and positions is not the same as showing energy units as having a particular place in the system at any given time, as is implied in Criterion G and H of the Gray Checklist.

In order to fulfill the Energy State constituent idea, I propose that a new criterion, Narrative Dimension, be created and added to the Gray Checklist. This criterion would be fulfilled when a diagram is organized with regard to a particular dimension, such as time or relative position, in order to show differences in energy quantities throughout the interaction that the diagram describes.

The Energy State constituent idea and its requisite new criterion, Narrative Dimension, is in line with the text of standard HS-PS-3-1, which stipulates that students should be able to

construct computational models of energy based on observable quantities, which can then help students track energy throughout a system. While the diagramming schemes described in this thesis are not computational in and of themselves, they allow for students to think critically about how to use a model to organize and track energy throughout a system. Not only do students need to decide what narrative dimension to use in order to do this tracking (for instance, students completing the Student Running Up Stairs prompt used either time or position), but students also need to choose the forms that best fit the situation for which they are making a diagram. Furthermore, the idea of constructing an organized narrative fits alongside the Systems and System Models and Stability and Change Crosscutting Concepts.

6.3 On Modality Considerations

This thesis investigation finds no needed changes to the Gray Checklist on account of shifts in modality. While the COVID-19 pandemic drastically changed the nature of the delivery of the classes described in this study, the diagrams produced followed the same protocols that were followed in the Spring of 2019. Furthermore, the initial diagrams produced in response to the Energy Diagram #1 prompt during the shift from in-person to online learning followed common conventions that were easily assessed using the Gray Checklist.

6.4 Implications for Teaching and Learning

This study bears with it several ideas and considerations for the teaching and learning of energy, specifically using energy diagrams and assessing them using a tool like the Gray Checklist. These implications for teaching and learning are outlined in this section.

6.4.1 The Gray Checklist as a Planning Document

The Gray Checklist is a useful bridge between the NGSS and the curricular choices a teacher makes with regard to lesson planning. Specifically, if a teacher chooses to use energy diagramming in their classes with the goal of helping students learn about energy in ways that align with certain standards and learning outcomes, then they can choose energy diagrams based on the constituent ideas and criteria that a particular diagramming scheme might fulfill. For instance, if a physics teacher wants to teach conservation of energy, an Energy Tracking Diagram would fit that curricular goal. However, using Energy Trajectory diagrams (or similar diagrams) does not fulfill the requisite criteria in order to achieve the Conservation of Energy constituent idea. Work could be done in the future to assess energy diagramming schemes with the Gray Checklist in order to give teachers a sense of which standards they might meet through the use of energy diagrams in their classes.

6.4.2 Performance Indicators

As discussed in Section 6.1, the Gray Checklist can detect evidence of certain elements of the NGSS energy model in student diagrams, but it does not assess the extent to which a particular energy diagram is realistic or adequately describes a particular situation to an audience, or helps a student communicate to an instructor whether or not they have an understanding of energy in a system with any fluency. Furthermore, meeting criteria in the Gray Checklist is not an indication that a student has demonstrated mastery of its constituent ideas; rather, it is merely evidence that the diagram indicates fulfillment of those ideas. Future work on the Gray Checklist can also include performance indicators that allow teachers to evaluate the quality of their students' diagrams in a way that aligns with scientific consensus. For example, could check the diagram for use of appropriate forms of energy in particular situations,

construction of energy tracks or energy change that reflects the behavior of the system, or for obeying specific laws regarding the energy concept as a whole (such as conservation of energy).

One specific example of where performance indicators could be particularly useful is in the assessment of the diagrams in the Pot of Boiling Water Prompt described in Section 4.2. While diagrams made in response to that prompt featured a diverse array of energy forms and energy tracks, the use of some forms of energy that directly relate to the process of heating water to its boiling point (like thermal or kinetic) may make more sense to the scenario than others that are better used in other scenarios (such as chemical or potential). While the water on the stove *does* have chemical energy stored in molecular bonds and potential energy on account of its relative height to a ground level, these energy forms might be considered trivial or redundant to the instructor, and do not factor into the actual process being described.

6.4.3 The Energy Model of the NGSS

The Gray Checklist attempts to encapsulate the entire model for energy laid out in the NGSS in order to distill that model into a useful assessment tool. However, the Energy Crosscutting Concept only tells part of the story with regard to the NGSS energy landscape. This thesis argues, in part, that energy is not only a series of metaphors that describe a series of abstractions, but is also a modeling process in and of itself, used to describe how systems either remain stable or undergo change. These areas are the bailiwick of the Systems and System Change and Stability and Change crosscutting concepts. Energy, and its use as a predictive idea in the sciences, is about systems and their interactions, and whether those interactions bring about changes within that system and in other adjacent systems. Future work on the Gray Checklist could also include searching for other constituent ideas and criteria that diagrams

might exhibit in regard to these crosscutting concepts that play a central role in the NGSS energy model.

6.5 Conclusion

For all its ubiquity and utility in the sciences, energy is at once real and constructed, tangible and ethereal. For all the places in which energy is scattered about the Next Generation Science Standards, our ability to work with, calculate, and track energy is highly dependent upon our fluency in its metaphorical language. No standard can impress the importance of this fluency upon the teachers who choose to stir energy into their interpretations of natural phenomena. To teach about energy is to serve as a user and a translator for this language, as well as to serve as the chief native speaker for classes of students. Likewise, to learn about energy is to be a visitor to a realm of physics that is, at its core, an abstraction that is as alive and real as our own representations allow.

Documents like the Gray Checklist are able to reach two different sets of teachers and connect them to the energy model that the NGSS proposes. First, this checklist allows physics teachers to incorporate energy diagramming schemes into their work with students in ways that both fit the scientific consensus on energy (as relayed by standards documents) and to connect the diverse understanding of energy that students may bring from other disciplines. Second, this document allows teachers in other disciplines to connect with the energy metaphors and analogies that are best suited for their disciplines, and allows them to understand how those metaphors fit into the broader picture of energy from a physical perspective. The Gray Checklist, and other such documents which help teachers and researchers make sense of the NGSS for purposes of instruction and assessment, have the potential to help science curricula achieve

narrative coherence while allowing teachers to make individual curricular decisions that suit their needs in the classroom.

Energy diagramming schemes like those discussed in this thesis are critical entry points for students in any discipline to navigate this deep, complex, and flexible lexicon. Just as Dennis the Menace and his mother pursue the location of his blocks in Feynman's Conservation of Energy lecture, energy diagrams are a tool that students can use to make sense of energy in a way that stays consistent to the metaphors appropriate to the phenomena. It is fitting that in the Energy Cubes representation mentioned by Scherr, et al. (2012), students are, quite literally, playing with blocks, making sure of where they are, what they are, and where they are meant to go over time.

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BIOGRAPHY OF THE AUTHOR

Michael Dudley was born in Olympia, Washington, on December 20, 1983. He graduated from Morse High School, in Bath, Maine, in 2001, and went on to study at the University of Maine, earning a BA in Physics in 2006 with a minor in Women's Studies. While at the University of Maine, Michael developed a passion for physics education, and the research involved in understanding student learning of physics. Michael presented his senior project in physics at the Summer Meeting of the American Association of Physics Teachers in 2005 on the transfer of student learning of equipotentials in mechanics to electrostatics.

Following his graduation from the University of Maine, Michael taught at a variety of schools throughout New England. His teaching assignments have included Noble High School in North Berwick, Maine (2006-2008); the Sizer School in Fitchburg, Massachusetts (2008-2013, 2014-2015); Innovation Academy Charter School in Tyngsboro, Massachusetts (2013-2014), and Virtual Learning Academy Charter School in Exeter, New Hampshire (2013-2015). In all of these schools, Michael worked on the cutting edge of education, creating project-based curricula, facilitating teacher-led professional development, and participating in STEM-focused professional development. Michael is a five-time recipient of the Sontag Prize in Urban Education; as a recipient, Michael taught acceleration academies in mathematics to underserved seniors at Lawrence High School and sophomores at Chelsea High School.

Currently, Michael works as a physics and engineering instructor in Bangor, Maine, and lives there with his wife, Shannon Levesque, and his daughter, Meredith Levesque. In addition to his professional pursuits, Michael loves playing and organizing chess events. He is a candidate for the Master of Science in Teaching degree from the University of Maine in 2021.