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BEYOND FORMS  
FINDINGS FROM A NEW  
APPROACH TO TEACHING ENERGY IN MIDDLE SCHOOL

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DISSERTATION  
ZUR ERLANGUNG DES DOKTORGRADES  
DER MATHEMATISCH-NATURWISSENSCHAFTLICHEN  
FAKULTÄT DER  
CHRISTIAN-ALBRECHTS-UNIVERSITÄT ZU KIEL

VORGELEGT VON

MARCUS KUBSCH

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## SUMMARY

Energy is an important concept across the sciences and for physics in particular. However, only few students develop an understanding of energy that includes the critical aspect of conservation and is well-organized. However, having well-organized ideas about energy is a prerequisite for applying that knowledge to make sense of phenomena.

While the difficulty of energy for students is well established, there is vigorous debate about how to teach energy. The conceptual foundation of traditional forms-based instruction has been challenged time and again. As an alternative to forms, a transfer-only perspective that does not require forms and emphasizes the connections between energy, systems, and fields has been proposed. This position has also been adopted by the *Framework for K-12 Science Education* (NRC, 2012). However, neither the *Framework for K-12 Science Education* nor the scholars that have argued for transfer-only approaches have provided any guidance for how the instructional challenge of introducing energy, systems, and fields – all difficult ideas – in introductory energy instruction, that is, in middle school, can be approached. As part of the ELeVATE project (Exploring Potential Trajectories for the Energy Concept in Middle School), a transfer-only unit was developed, following the principles of project-based learning. Drawing on data from the ELeVATE project, this dissertation investigates how students build ideas about energy in the transfer-only unit and how they can be supported in doing so.

The findings indicate that students successfully build a well-organized understanding of energy, including a qualitative notion of energy conservation, that allows them to use this knowledge to make sense of various phenomena. This suggests reconsidering the paradigm of energy learning progressions having to go through forms, highlights the power of coherent curriculum that project-based learning facilitates, and underlines the importance of having well-organized knowledge for being able to apply that knowledge.

## ZUSAMMENFASSUNG

Energie ist eine zentrale Idee in den Naturwissenschaften und fundamental für die Physik, stellt jedoch für Lernende eine große Herausforderung dar. Nur wenige Lernende entwickeln ein Energieverständnis, das Energieerhaltung beinhaltet und gut vernetzt ist. Ein gut vernetztes Wissen über Energie ist jedoch Grundlage für Kompetenz, d.h., die Anwendung des Wissens.

Während Einigkeit besteht, dass das Energiekonzept herausfordernd ist, besteht großer Dissens darüber, wie Energie unterrichtet werden soll. Die Idee von Energieformen, traditionell Grundlage des Energiebegriffs, wird dabei immer wieder für Lernschwierigkeiten verantwortlich gemacht. Als Alternative wird vorgeschlagen, auf die Idee des Energietransfer zu fokussieren und auf die Verbindungen zwischen Energie, Systemen, und Feldern einzugehen ohne Formen einzuführen. Diese Position wurde auch vom *Framework for K-12 Science Education* (NRC, 2012) adaptiert. Allerdings geben weder das *Framework for K-12 Science Education* noch Autoren, die für einen Fokus auf Transfer argumentieren, Hinweise wie man der Herausforderung begegnen kann, im Einführungsunterricht – also in der Mittelstufe – Energie, Systeme und Felder zu behandeln. Im Rahmen des ELeVATE Projekts (Exploring Potential Trajectories for the Energy Concept in Middle School) wurde auf Basis von *Project-based learning*, eine Unterrichtseinheit entwickelt, die auf Transfer fokussiert. Basierend auf Daten aus dem ELeVATE Projekt, untersucht diese Dissertation wie Lernende ein Verständnis von Energie in dieser Unterrichtseinheit entwickeln und wie sie dabei unterstützt werden können.

Die Ergebnisse zeigen, dass Lernende ein gut vernetztes Verständnis von Energie, inklusive eines qualitativen Erhaltungsbegriffs, entwickeln, das ihnen erlaubt, dieses Wissen anzuwenden. Dies hinterfragt das Paradigma des formenbasierten Unterrichts, demonstriert die Effektivität von kohärenten Unterrichtsgängen basierend auf *Project-based learning* und unterstreicht die Bedeutung eines gut vernetzten Wissens für die Entwicklung von Kompetenz.

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## INTRODUCTION

Energy is a fundamental idea across the sciences and for physics in particular as it provides an important lens to gain insight into phenomena. However, students struggle to develop an understanding of energy, especially the aspect of energy conservation (Herrmann-Abell & DeBoer, 2017; Lee & Liu, 2010; X. Liu & McKeough, 2005; Neumann, Viering, Boone, & Fischer, 2013). Further, there is vigorous debate about how students can develop an understanding of energy, i.e., “about what to teach about energy when and how” (Papadouris & Constantinou, 2016, p. 1). Traditionally, curricula present energy as being manifest in different forms, consequently progressing to transformations and transfer of energy (Kaper & Goedhart, 2002). However, the conceptual basis of forms-based approaches has repeatedly been criticized (Doménech et al., 2007; Ellse, 1988; Falk, Herrmann, & Schmid, 1983; Kaper & Goedhart, 2002; R. Millar, 2011; Swackhamer, 2005). As an alternative numerous scholars have proposed to focus on energy transfers between systems (Brewer, 2011; Ellse, 1988; Falk et al., 1983; Lehavi & Eylon, 2018; Swackhamer, 2005; Millar, 2005). A main difference between these proposals is to what extent they abandon forms, i.e., whether they use forms language at some point or remain in a strict transfer-only framework, emphasizing the unitary nature of energy. Swackhamer (2005) and the *Framework for K-12 Science Education* (National Research Council, 2012) emphasize the unitary nature of energy. Further, they emphasize the connections between energy, systems, and fields that mediate interaction-at-a-distance. This sets up the instructional challenge of addressing three complex ideas – energy, systems, and fields that mediate interaction-at-a-distance – in introductory energy instruction in middle school. However, neither Swackhamer (2005) nor the *Framework for K-12 Science Education* (National Research Council, 2012) provide any guidance on how to approach this instructional challenge. The ELEVATE project (Exploring Potential Trajectories for the Energy Concept in Middle School) set out to develop a transfer-only unit (Nordine, Fortus, Lehavi, Neumann, & Krajcik, 2019) for the middle school level – the systems-transfer

unit – and contrast it with a comparable forms-based unit. Drawing on data from the ELEVATE project, this dissertation investigates how students build ideas about energy in the systems-transfer unit and how they can be supported in doing so.

### **DEVELOPING AN UNDERSTANDING OF ENERGY - GOALS FOR ENERGY INSTRUCTION**

Following research that clearly shows that the learning of science content cannot be separated from the doing of science, modern science standards such as the *Next Generation Science Standards* (National Research Council, 2007) or the German *Bildungsstandards* (Sekretariat der ständigen Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland, 2004) emphasize that students should not only develop knowledge *about* science ideas but be enabled to *use* that knowledge to make sense of phenomena. To demonstrate such a knowledge-in-use (Harris, Krajcik, Pellegrino, & McElhaney, 2016) about energy requires that students have well-organized knowledge networks about energy as those are a prerequisite for fluent application and retrieval (Bransford, 2000). The knowledge-integration perspective (Linn, 2006) emphasizes the importance of well-organized knowledge networks and views learning as a process of developing increasingly connected and coherent sets of ideas. Connecting ideas appears especially important with respect to energy, as it is a complex concept with many aspects and rich connections to other science ideas such as force. For example, if one learned only about forms of energy but was not able to connect forms to transformation ideas, one would struggle to use this knowledge to make sense of phenomena.

Building coherent connections between ideas however is a process that takes time and instruction that provides opportunities for students to establish these connections (Linn, 2006; National Academies of Sciences, Engineering, and Medicine, 2018; Sikorski & Hammer, 2017) and see their explanatory value (Smith III, diSessa, & Roschelle, 1994). This time and effort however is worthwhile because having integrated knowledge supports future learning, that is, knowledge-transfer (Bransford & Schwartz, 1999), both

within and across domains, e.g., well-organized knowledge networks can provide a structure for adding new knowledge elements or help to identify familiar structures in new contexts and content areas (Bransford, 2000; Chi, Feltovich, & Glaser, 1981; National Academies of Sciences, Engineering, and Medicine, 2018). This is also reflected in educational standards. Energy serves as one of four core ideas in physical science and as a cross-cutting concept in the U.S. *Framework for K-12 Science Education* (National Research Council, 2012). Further energy is a *Basiskonzept – basic concept* – in physics and chemistry, and an important constituent of the basic concepts in biology in the German *Bildungsstandards* (Sekretariat der ständigen Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland, 2004). Core and cross-cutting ideas as well as basic concepts are supposed to organize curriculum so that students can develop integrated knowledge to support future learning within as well as across domains.

Having discussed that energy is a complex concept with many interconnected aspects, the question arises which aspects and connections are especially important for developing knowledge-in-use about energy, i.e., using energy ideas to make sense of phenomena. The following example of the prediction of the neutrino by Wolfgang Pauli does not only highlight the usefulness of energy in physics but also illustrates how the aspect of conservation and the connection between energy and systems is especially important. In the early 20<sup>th</sup> century, physicists struggled to make sense of the observed continuous energy spectra of electrons in beta decay. Single electrons appeared to be the sole decay product in beta decay and thus the principle of energy conservation demanded the whole energy of the decaying particle to be found in the resulting electron. Therefore, physicists expected to find well-defined discrete energy spectra. At this point, there are two ways to resolve the conundrum: abandoning strict energy conservation as Niels Bohr suggested, or introducing a process by which energy could be transferred to some other system. In 1930, Wolfgang Pauli suggested the latter. He proposed a new particle, later coined neutrino by Enrico Fermi, to be emitted together with the electron in beta decay. When different amounts of energy are transferred

to the neutrino, electrons can be emitted at different energies and thus produce continuous spectra. The neutrino was eventually detected experimentally in 1956 (Cowan, Reines, Harrison, Kruse, & McGuire, 1956). This episode highlights that energy provides a powerful lens that is especially helpful when one has little or no knowledge about a phenomenon. Energy conservation generally applies, and a seeming violation of energy conservation implies that there are systems, processes, and transfers one has not yet accounted for.

In sum, to develop knowledge-in-use about energy and support future learning, instruction needs to support students in building an integrated knowledge about energy that emphasizes the connections between systems, processes, and transfers and their close connection to the idea of conservation (Nordine et al., 2019). To do so, students need to activate a coherent set of ideas in a variety of contexts where those ideas have explanatory value. With this goal for energy instruction set, the question becomes what is known about how students learn about energy because research into students learning about should inform the design of instruction.

### **LEARNING ABOUT ENERGY – THE STATE OF AFFAIRS**

Students' learning about energy is often described relative to a number of constituent ideas or aspects of the energy concept. While the exact number of aspects differs as they are combined in different ways, the most basic aspect is often devoted to the different ways in which energy is manifest in phenomena, and the most abstract and fundamental aspect is energy conservation (Duit, 1986). Between manifestations and conservation, energy transfer and transformation as well as degradation and dissipation can be distinguished and to what extent they are combined or considered individually is a question of grain size and learning environment, e.g., Neumann et al. (2013) combine transfer and transformation whereas Herrmann-Abell & DeBoer (2017) combine forms and transformations and treat transfer individually. Empirical research into energy learning progressions aligns with this picture of fixed ends and a fuzzy middle ground: items that test students' knowledge about forms are clearly easiest, items about conservation are clearly hardest, and items

about transfer, transformation, dissipation and degradation are somewhere in between and largely overlap in difficulty (Herrmann-Abell & DeBoer, 2017; X. Liu & McKeough, 2005; Neumann et al., 2013; Park & Liu, 2019). While this line of learning progressions research mostly addressed students' mastery of individual aspects, another line investigated to what extent students have integrated knowledge about energy. Numerous findings indicate that students rarely connect multiple energy aspects to make sense of phenomena but rather rely on single aspects, i.e., only few students do develop integrated knowledge about energy (Kauertz & Fischer, 2006; Lee & Liu, 2010; O. L. Liu, Ryoo, Linn, Sato, & Svihla, 2015; Nordine, Krajcik, & Fortus, 2011). A caveat of most of the aforementioned studies is that they had no deliberate instructional component, i.e., teacher and curriculum effects are not considered but effectively averaged. Thus, individual potentially effective teaching approaches and alternative progressions are possibly filtered (Duncan & Hmelo-Silver, 2009; Duncan & Rivet, 2013). Further, those studies mostly drew on content focused, multiple choice or short constructed response assessments. Thus, the integration of content knowledge and scientific practices, i.e., knowledge-in-use, was not assessed.

Students' struggles with energy are often attributed to the abstractness of the concept (Harrer, 2017) and competing everyday notions of energy (Lancor, 2015; Watts, 1983) that lead to students' struggling with conceptualizing energy (Duit, 2014) and confusing it with related ideas such as force or power (Osborne & Gilbert, 1980; Viennot, 1979). Another source of confusion is that different disciplines use different metaphors to talk about energy. Even within physics different metaphors are used in the various sub-fields. For example, quantum physics often uses a spatial metaphor, talking about e.g., an electron being at different energy *levels* whereas in classical mechanics a container metaphor is often used when the amount of energy that is *in* a system is discussed (Harrer, 2017). This can lead to students' conceptualizing energy differently in different contexts (Opitz, Blankenstein, & Harms, 2017; Park & Liu, 2016) and may interfere with students building an integrated understanding of energy. Lastly, some scholars have also

questioned to what extent the conceptual foundations of energy, specifically the idea of energy forms, contribute to students difficulties (Ellse, 1988; Falk et al., 1983; Swackhamer, 2005). As forms are “not generally well-defined” (Quinn, 2014, p. 19), they may invoke multiple and conflicting ontologies for energy which in consequence may impede future learning (Reiner, Slotta, Chi, & Resnick, 2000).

In summary, learning progressions research suggests that students understanding of energy progresses from forms through transfer and dissipation to conservation. However, only few students develop an understanding of conservation and students struggle to connect the different aspects of energy to explain phenomena, that is, to develop an integrated knowledge. These struggles with the energy concept may be attributed to the many abstract and sometimes conflicting notions of energy that make it difficult to build a coherent, well-organized set of ideas around energy.

#### **A NEW APPROACH TO TEACHING ENERGY**

So far, I have argued that energy instruction that supports students in developing integrated knowledge about energy as a prerequisite for knowledge-in-use, should emphasize that students build a coherent set of ideas that they apply in a variety of contexts in which these ideas have explanatory value. Research into students learning suggests that students in instruction that emphasizes the ideas of forms and transformations rarely develop integrated knowledge. So, what might be energy ideas that students can integrate more easily into a coherent set and what pedagogical approaches can support students in building this set?

#### ***A COHERENT SET OF IDEAS – THE TRANSFER-ONLY APPROACH***

The transfer-only approach connects three challenging ideas - systems, energy, and fields. However, it does so in a very coherent way that avoids problems that the traditional forms-based approach has. Forms-based approaches can appear incoherent in their ontologies because when one talks



about energy being transferred, e.g., in a collision, one clearly invokes a substance ontology. However, when one talks about a transformation, it is rather a process ontology. Reiner et al. (2000) provide a list of empirically backed properties that a substance ontology invokes. Many of these features are useful when one uses them to think about energy, e.g., conservation or locality (Brewer, 2011; Duit, 1987; Scherr, Close, McKagan, & Vokos, 2012; Swackhamer, 2005). However, "transformation" is not part of this list. This may lead to ontological confusion and could well explain the finding that students are prone to consider individual forms conserved (Nordine et al., 2011) as talking about a transfer of e.g. kinetic energy is consistent with a substance ontology for that individual form of energy and thus implies that individual forms are conserved.

A similar problem can easily occur with potential energy. While kinetic energy is usually clearly localized in an object, potential energy cannot be localized in a single object as it is tied to the spatial configuration of a *set of objects*. However, since the connection between energy and systems is rarely made in instruction (Jewett, 2008), potential energy often lacks a place in students' mental models (Quinn, 2014). Further, ignoring this connection leads to the incoherence of energy sometimes being localized and sometimes not. Indeed, potential energy is considered one of the more challenging aspects of energy (Cooper & Klymkowsky, 2013; Hecht, 2003; Herrmann-Abell & DeBoer, 2017).

In contrast, a transfer-only approach always corresponds to a substance ontology and when one emphasizes the connections between energy, systems, and fields, one can localize potential energy in the field (National Research Council, 2012; Scherr et al., 2012; Swackhamer, 2005). Thus, while systems, energy, and fields, are considered challenging ideas on their own (Furio & Guisasola, 1998; Lindsey, Heron, & Shaffer, 2012), they form a coherent set of ideas to make sense of phenomena. The remaining question is whether these ideas can be made accessible in introductory energy instruction, that is, in middle school.

**PROJECT-BASED LEARNING – BUILDING A COHERENT SET OF IDEAS IN MEANINGFUL CONTEXTS**

Project-based learning is a form of situated learning (Greeno, 2006), i.e., it emphasizes that learning requires the active construction of knowledge by *using* ideas in meaningful contexts. Therefore, project-based learning clearly aligns with the goal of knowledge-in-use and should provide opportunities that support knowledge integration when students use a set of ideas across a variety of contexts. The contexts are tied together by a driving question (and potentially numerous sub driving questions, depending on the length of the unit) that guides instruction. Driving questions help that students develop a need-to-know, i.e., they elicit a desire to learn and make students realize that there is an important problem that genuinely needs to be solved (Krajcik & Shin, 2014). Thus, using energy ideas to make sense of a driving question and its sub components provides opportunities to use energy ideas in a variety of contexts in which they have explanatory value, i.e., answering driving questions should support knowledge integration. However, the need-to-know also helps to focus instruction. When there needs to be a need-to-know for every new idea that is introduced, this helps to only introduce *really* necessary ideas and only *really* needed complexity. Avoiding potentially interesting but ultimately not relevant detours helps to maintain coherence between ideas and to avoid curricula that are mile wide but only inch deep (NCES, 1996).

Another feature of project-based learning that is important in the context of energy is its emphasis on using tools such as representations because especially in energy instruction, the use of representations is ubiquitous. Representations support learning in many ways such as helping to establish a need-to-know, e.g., when they “show” that an existing model does not explain a new phenomenon and thus needs to be revised. However, excluding mathematical representations of energy such as  $E = mc^2$ , there is no consensus representation for energy (in contrast to free-body diagrams for forces) and consequently a variety of representations exists and is commonly used

(Ametller & Pintó, 2002; Scherr et al., 2012). Albeit, there is little empirical research into the effectiveness of different representations in supporting students, especially not when it comes to comparing different representations. A number of studies show examples of how students use representation to successfully make sense of phenomena (Barth-Cohen & Wittmann, 2017; Papadouris & Constantinou, 2016; Tobin, Lacy, Crissman, & Haddad, 2018; van Heuvelen & Zou, 2001) but present no examples of how students make sense of phenomena without the respective or a different representations. Thus, arguments in favor of specific representations remain mostly theoretical and rely on anecdotal evidence. The theoretical arguments often compare to what extent specific representations represent constituent ideas of a given energy model (Gray, Wittmann, Vokos, & Scherr, 2019; Scherr et al., 2012), e.g., whether energy bar charts represent forms of energy. A potential problem with this approach is that this judgement is often made by researchers, usually experts in the domain, and not students. Therefore, it remains uncertain whether students really recognize these features or whether they are only apparent to experts. For example, Gray et al. (2019), argue that an energy flow diagram represents conservation because the total width of the arrows that represent energy flow is constant but present no evidence that students a) notice this feature and b) connect it to the idea of conservation. While the general effectiveness of supporting students with representations is firmly established in the psychological and educational literature (Ainsworth, Prain, & Tytler, 2011; Mayer, 2014; Paivio, 1986), it appears that the effectiveness of specific energy representations needs to be put on more solid empirical ground.

In sum, the transfer-only perspective represents a coherent set of ideas and applying them in relevant contexts should help students to develop integrated knowledge and consequently knowledge-in-use about energy. The principles of project-based learning help to focus on a coherent set of ideas and provide opportunities to apply them in relevant contexts.



## GOALS & OUTLINE

The systems-transfer unit developed in the ELeVATE project is a transfer-only unit that emphasizes the connections between energy, systems, and fields. It was developed following the principles of project-based pedagogy. As such, it should support students in developing knowledge-in-use about energy. The following publications investigated how students build ideas about energy in the systems-transfer unit and how they can be supported in doing so.

### **PUBLICATION I: IN PRAISE OF MODEST GOALS – CONNECTING ENERGY, SYSTEMS, AND FIELDS IN MIDDLE SCHOOL**

This publication looks at learning within the systems-transfer unit. Drawing on data from two consecutive enactments we have investigated how differently achieving students use of systems, transfer, and fields ideas develops over the course of the unit. We found that at the end of the unit, students use systems, energy, and fields ideas in a way that aligns with a substance-like model of energy which entails a qualitative notion of conservation. With respect to fields, we found macroscopic fields to be more accessible in middle school than microscopic and students still struggling with correctly determining the direction of energy transfer as well as the process related to energy transfer. Lastly, we found no evidence for an interaction between students' general achievement level and their progress over the course of the unit. We discuss our results with respect to their implications for energy learning progressions, the substance-like model promoting an understanding of conservation, and the utility and accessibility of fields ideas.

### **PUBLICATION II: SUPPORTING STUDENTS IN USING ENERGY IDEAS TO INTERPRET PHENOMENA: THE ROLE OF AN ENERGY REPRESENTATION**

Typical for energy instruction is the use of pedagogical representation to make the abstract concept of energy more tangible and thus support students. However, a review of existing representations of energy showed that

none emphasized *all* energy ideas needed in the systems-transfer approach and most emphasized forms. Further, the effectiveness of existing representations in supporting students appeared mostly to be supported by anecdotal evidence. Publication II addresses this issue by investigating the effectiveness of a newly developed representation called *Energy Transfer Model* in supporting student to use energy ideas to make sense of phenomena. Using a quasi-experimental design and drawing on the framework of cognitive tools, we found evidence that constructing an Energy Transfer Model supported students in making sense of phenomena, i.e., in identifying hidden systems and processes. We discuss what our results imply for different notions of conservation, usage of energy representations and cognitive tools more broadly, and future research on representations.

### **PUBLICATION III: PROBING THE RELATION BETWEEN STUDENTS' INTEGRATED KNOWLEDGE AND KNOWLEDGE-IN-USE ABOUT ENERGY USING NETWORK ANALYSIS**

Integrated knowledge is a prerequisite for knowledge-in-use. This publication investigates to what extent students in the systems-transfer unit developed integrated knowledge about energy and how it is related to students' knowledge-in-use about energy. To do so, we researched to what extent students build well-organized knowledge-networks around energy in the systems-transfer unit and to what extent those knowledge-networks support students in applying those ideas to make sense of phenomena. To investigate students' knowledge networks, we applied an innovative network analytical technique and to investigate students' ability to use those ideas we drew on knowledge-in-use assessments. We found that students develop well-organized knowledge networks and that the degree of organization is related to students' ability to use energy ideas to make sense of phenomena. We discuss our results with respect to the concept of core ideas in science standards, the relation of content and practices in science learning, and approaches to measuring the organization of students' ideas.

**PUBLICATION IV: DER SYSTEM-TRANSFER-ANSATZ**

This publication aims at disseminating the systems-transfer perspective among teachers in Germany. It sketches how the main ideas of the systems-transfer perspective – systems, transfer, fields – can be motivated and introduced in middle school energy instruction and how the systems-transfer perspective can help students to align the everyday notion of energy being “used up” in dissipative processes with the idea of energy conservation.





## **PUBLICATION I:**

### **IN PRAISE OF MODEST GOALS - CONNECTING ENERGY, SYSTEMS, AND FIELDS IN MIDDLE SCHOOL**

#### **ABSTRACT**

Scholars have repeatedly criticized the conceptual foundation of forms-based energy instruction. We developed a new approach that does not require forms and builds on the recommendations in the *Framework for K-12 Science Education* (National Research Council, 2012) and the *US Next Generation Science Standards* (NGSS Lead States, 2013) to emphasize connections between energy, systems, and fields that mediate interaction-at-a-distance – three complex ideas that are challenging on their own. In this paper we report on a study where we tracked students' learning during two enactments of the approach to investigate how students' usage of systems, transfer, and fields develops over the course of the systems-transfer unit. We found that at the end of the unit, students use systems, energy, and fields ideas in a way that aligns with a substance-like model of energy which entails a qualitative notion of conservation. While students readily use fields ideas, we found macroscopic fields to be more accessible than microscopic fields. We discuss implications for energy learning progressions, the substance-like model promoting an understanding of conservation, and the utility and accessibility of fields ideas.

**INTRODUCTION**

Energy is a central idea across the sciences (Chen et al., 2014) and key to understanding global issues such as climate change (Mittenzwei, Bruckermann, Nordine, & Harms, 2019; U.S. Global Change Research Program, 2009). However, there is ample evidence that students struggle to develop a full understanding of energy during K-12 education (Herrmann-Abell & DeBoer, 2017), especially about the idea at the heart of the energy concept – conservation (Harrer, 2017).

While there is broad consensus about the importance and notorious difficulty of the energy concept, researchers disagree about “what to teach about energy when and how” (Papadouris & Constantinou, 2016). A major schism exists between approaches that present energy as manifest in forms (e.g., Krajcik, Reiser, Sutherland, & Fortus, 2012) and those that present energy as unitary (e.g., Swackhamer, 2005). Whereas many approaches to teaching energy present energy as manifest in different forms (Kaper & Goedhart, 2002), scholars have repeatedly criticized the conceptual foundation of forms-based approaches to teaching energy (Doménech et al., 2007; Ellse, 1988; Falk, Herrmann, & Schmid, 1983; Kaper & Goedhart, 2002; Millar, 2011; Swackhamer, 2005), especially for potentially impeding students in developing an understanding of conservation. As an alternative it has been proposed to emphasize the unitary nature of energy and focus on transfers of energy between systems (Brewer, 2011; Ellse, 1988; Falk et al., 1983; Swackhamer, 2005) – a position which has also been adopted by the Framework for K-12 Science Education (National Research Council, 2012). Theoretically, focusing on transfer of energy between systems may support students in developing the idea of conservation (Brewer, 2011; Falk et al., 1983; Harrer, 2017; Swackhamer, 2005). However, applying such a systems-transfer perspective consistently in phenomena that involve interaction-at-a distance requires to introduce fields – which researchers have found to be a challenging concept for students (Furio & Guisasola, 1998). Rather than introducing fields, instructional approaches that emphasize transfer either try to avoid phenomena that

involve interaction-at-a distance (Papadouris & Constantinou, 2016) or use forms in such cases (Millar, 2011).

Based on the recommendations of the Framework for K-12 Science Education (National Research Council, 2012) and the U.S. Next Generation Science Standards (NGSS Lead States, 2013), we have developed a middle school energy unit that treats energy as unitary and emphasizes the connections between energy, systems, and fields (Nordine, Fortus, Lehavi, Neumann, & Krajcik, 2019). We approached the challenge of addressing energy, systems, and fields following two principles: 1) only introducing the absolutely necessary ideas, and 2) introducing new concepts so that they answer a need-to-know. In this paper, we explore students' learning within the unit to investigate how students' usage of systems, transfer, and fields develops as the unit progresses and discuss consequences for energy learning progressions, the utility and accessibility of fields ideas, and the how treating energy as unitary may promote nas-cent conservation ideas.

## **BACKGROUND**

### ***TEACHING AND LEARNING ABOUT ENERGY***

Whereas energy is a fundamental concept in physics and a central idea across the sciences, numerous studies have shown that students struggle with the energy concept, e.g., with conceptualizing energy (Duit, 2014), especially potential energy (Cooper & Klymkowsky, 2013), with systems thinking in the context of energy (Lindsey, Heron, & Shaffer, 2012), with applying energy ideas to make sense of phenomena (Driver & Warrington, 1985). Few students develop a full understanding of the energy concept, and most particularly struggle with the important aspect of conservation (Herrmann-Abell & DeBoer, 2017; Lee & Liu, 2010; Neumann, Viering, Boone, & Fischer, 2013). Moreover, students apparently fail to see the usefulness of the energy concept to make sense of phenomena, as even students that have a sufficiently developed understanding of energy, rarely opt to use energy ideas (Chabalengula, Sanders, & Mumba, 2012).

Various instructional approaches have been proposed to answer the instructional challenge that energy poses. While some of this variety comes from different pedagogical approaches such as emphasizing the history and epistemology of energy (Bächtold & Munier, 2018; Michel & Neumann, 2016; Papadouris & Constantinou, 2016), a more fundamental demarcation line is drawn between approaches that present energy as being manifest in different forms and those that present energy as unitary.

***Forms-based approaches - simple at first, misleading in the end?*** Traditionally, curricula present energy as being manifest in different forms, consequently progressing to transformations and transfer of energy. Forms appear appealing as they provide a straightforward way to talk about energy (Quinn, 2014) and connect to students' prior knowledge about energy, when introducing kinetic energy, one can build on students often already connecting energy to movement (Watts, 1983). Further, learning progressions research indicates that forms are the easiest aspect of energy (Herrmann-Abell & DeBoer, 2017; Liu & McKeough, 2005; Neumann et al., 2013). However, the same learning progressions research also indicates that only few students develop an understanding of conservation in forms-based approaches.

Forms-based approaches have been criticized for promoting labeling instead of conceptual understanding (Swackhamer, 2005), misleading students to conceptualize energy potential energy as a property of objects rather than systems (Doménech et al., 2007) or something that has the potential to become energy (Hecht, 2003), and implying to students that forms are conserved individually. Thus, forms may impede future learning, especially about conservation (Kaper & Goedhart, 2002). More fundamentally, forms have been criticized as "not generally well-defined" (Quinn, 2014, p. 19), a position adopted in the Framework for K-12 Science Education (National Research Council, 2012).

In sum, the seeming simplicity of forms is appealing from an instructional perspective, but if forms are responsible for students' difficulties with

conservation, e.g., students considering individual forms of energy conserved (Nordine, Krajcik, & Fortus, 2011) this simplicity comes at a high cost.

***Unitary approaches – challenging but worthwhile?*** Unitary approaches emphasize the unitary nature of energy and transfers of energy between systems. In the context of energy, systems are conveniently defined as parts of the world of interest in the phenomenon under study, i.e., entities that energy can be transferred to or from (Jewett, 2008). This definition also aligns with the one given by the Framework for K-12 Science Education (National Research Council, 2012). While this definition of systems appears simple in contrast to what is often associated with systems (Assaraf & Orion, 2005), the connection to systems in unitary approaches may still be considered a potential hurdle, especially for lower achieving middle school students, as even university students are known to struggle with systems in the context of energy (Lindsey et al., 2012).

Focusing on transfers of energy between systems aligns with a substance-like model of energy which is consistent with how physicists conceptualize energy (Harrer, 2017). The appeal of the substance-like model is that it allows students to use a matter metaphor (Lakoff, 1993). The long learned and familiar reasoning patterns for matter entail two ideas critical to energy: conservation and localization (Brewer, 2011; diSessa, 1993; Scherr, Close, McKagan, & Vokos, 2012). To illustrate this point, consider a collision between two balls A and B. When ball A collides with ball B, energy is transferred from ball A to ball B. In turn, ball A slows down and ball B speeds up. In this account, energy is always clearly located in either ball A or ball B. In addition, energy is conserved as energy always have to specify where the energy is coming from or going to, i.e., energy cannot come from or go to “nowhere”. This is further reflected by the fact that the processes that ball A and ball B undergo – slowing down and speeding up – are balanced, i.e., for every increasing process, there is a decreasing process. Indeed, empirical evidence suggests that the substance-like model supports students in developing an understanding of conservation (Kesidou & Duit, 1991). The main criticism of

the substance-like model is the concern that it may promote the conception that energy is a substance (Duit, 1987). However, as Scherr et al. (2012) point out there is no evidence that supports this assertion.

Whereas various instructional approaches emphasize the transfers between systems and thus align to a substance-like model (Ellse, 1988; Millar, 2011; Papadouris & Constantinou, 2016), they use forms when discussing phenomena that involve interaction-at-a distance or simply stay away from such phenomena. The reason for this is connected to the nature of potential energy which is inherently systemic and thus can hardly be attributed to a single entity. Consider a forms-based description of a falling ball to illustrate this point: potential energy is trans-formed into kinetic energy as the ball speeds up and gets closer to the Earth. Kinetic energy can be attributed to the ball which speeds up but where is potential energy localized? The forms-based description did simply not localize potential energy, which may actually be why students struggle with potential energy as it has no place in their mental models (Quinn, 2014). If forms-based approaches localize potential energy, it is often wrongly attributed to the ball which also leads to problems in making sense of phenomena using energy (Jewett, 2008). In a unitary-approach, we have to localize energy but as it is a systemic quantity, we can neither attribute it to the ball or the Earth alone. To address this problem, one can say that the energy that is transferred to the ball is coming from the Earth/ball gravitational field (Gray, Wittmann, Vokos, & Scherr, 2019; National Research Council, 2012; Quinn, 2014; Scherr et al., 2012; Swackhamer, 2005). The necessity to introduce fields explains why it is appealing to use to forms. Forms appear conceptually simple why fields have been found to be challenging for students (Furio & Guisasola, 1998; Pocoví, 2007; Rainson, Tranströmer, & Viennot, 1994; Saarelainen, Laaksonen, & Hirvonen, 2007; Saarelainen et al., 2007). However, the literature that shows that fields are challenging has focused on fields when they are introduced in the context of force, typically as mathematical abstraction (see e.g., Halliday, Resnick, & Walker, 2005). Little is known about what students can achieve when fields are introduced in the context of energy but the main ideas about fields that

are needed – fields are entities in space that mediate interaction-at-a distance to which energy can be transferred to or from – appear accessible in middle school (Atkin & Karplus, 1962; Bar, Zinn, & Rubin, 2007; Bradamante & Viennot, 2007).

In sum, unitary approaches potentially support students in developing an understanding of conservation – the central aspect of energy – as they align to a substance-like model of energy. However, they come at the cost of introducing fields and systems ideas and potentially fostering the idea that energy is a substance. Systems and especially fields are considered challenging, which may potentially be an additional burden on lower achieving students, but little is actually known about what students can learn about fields in the context of energy, as even approaches that prioritize transfer also incorporate forms, e.g., to discuss phenomena that involve interaction-at-a distance. This, in time, may undermine the potential benefits of unitary approaches as students are known to struggle with potential energy and these struggles in turn may at least partially be responsible for students struggling with the idea of conservation.

### ***RESEARCH QUESTION***

As part of a larger study that compares and contrast different approaches to teaching energy in middle school, we developed a unitary approach that introduces fields – the systems-transfer unit. To investigate what students in a unitary approach to teaching energy can achieve we ask the following research question: How does students' use of systems, transfer, and fields to make sense of phenomena develop over the course of the systems-transfer unit?

### ***THE SYSTEMS-TRANSFER UNIT***

In this section, we provide a summary of the systems-transfer unit (see Nordine et al. (2019) for a more complete description of this approach) as it

was taught in the two enactments (2017 and 2018), upon which the analyses of this article are based.

Following a design-based research approach, allowing for data-driven revisions between enactments, the 10-week systems-transfer unit was designed as a replacement for the 7<sup>th</sup> grade energy unit (Fortus et al., 2012) in the INVESTIGATE curriculum (Krajcik et al., 2012). In consequence, it follows project-based pedagogy (Krajcik & Shin, 2014), i.e., it is designed to build up students' knowledge systematically and coherently over time. This is achieved, for example, through a unit-level driving question "Why do some things stop and others keep going?", which is regularly revisited as the unit progresses. Further, the unit was designed to allow three-dimensional learning by integrating scientific practices, disciplinary core ideas, and cross-cutting concepts.

As systems and fields are known to be challenging ideas, we followed two design principles to introduce these ideas: 1) we only introduced the absolutely necessary fields and systems ideas, and 2) designed the curriculum so that fields are introduced to answer a perceived need-to-know.

While the unit generally focuses on the vision of three-dimensional learning (Krajcik, 2015), i.e., integrating scientific practices with disciplinary knowledge to learn about phenomena, across all scientific practices. The systems-transfer unit emphasizes the practice of modelling by engaging students in a representation called Energy Transfer Model (ETM, see Figure 1 for an example). Students construct ETMs throughout the unit to interpret and explain increasingly complex phenomena. Despite increasing in complexity throughout the unit, the ETMs always encompass three main components: The systems between which energy is transferred (solid-line boxes), the energy transfer (arrows between systems), as well as the occurring (both observable and non-observable) processes (in square brackets).



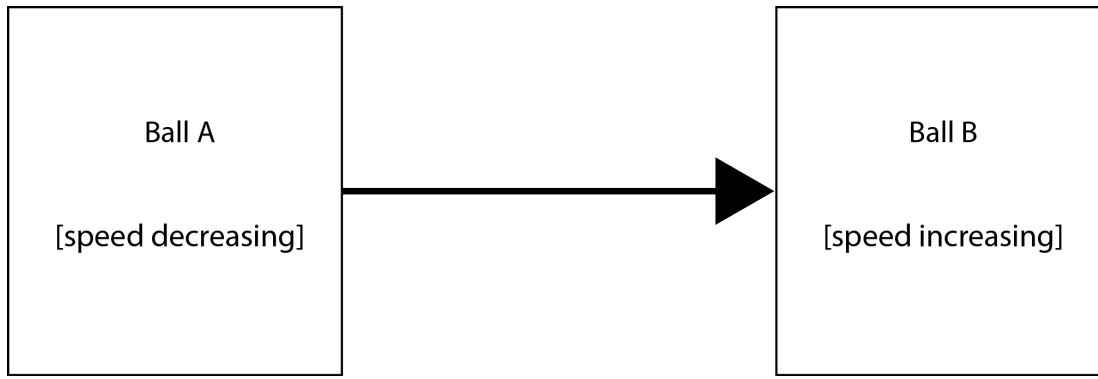


Figure 1. ETM for two balls A and B colliding. The boxes represent the systems, the arrow represents the direction of energy transfer, and the text in brackets describes the energy related processes in the systems.

The unit develops the ideas of energy, systems, and fields across four learning sets (LS) during which these ideas are used to interpret increasingly complex phenomena (Table 1).

**LS 1: modeling interactions between systems.** In this learning set, students learn that every phenomenon involves at least two interacting systems that each undergo some process. In line with the *Framework for K-12 Science Education* (National Research Council, 2012), systems are effectively defined as the relevant parts of the world under study. Students use a simplified version of an ETM to construct and refine simple models of phenomena that represent the interacting systems, how the systems interact, and the processes that occur in the interacting systems.

**LS 2: modelling balanced processes.** Here, students take a closer look at the processes in the interacting systems and learn to connect them to changes in energy and, subsequently, energy transfers between systems. Thus, the definition of systems is slightly extended to emphasize that energy can be transferred to or from systems. A series of investigations allows students to recognize that, anytime energy is transferred to/from one system, it must have been transferred from/to another system that undergoes an opposite energy change. Thus, a first implicit notion of energy conservation is introduced. At the end of learning set 2, students should be able to represent the interacting systems, processes, and energy transfers in various phenomena such as in Figure 1 using the ETM.

In sum, Learning Sets 1 and 2 effectively serve to develop a substance-like model of energy, emphasizing that energy is localized and always has to go or to come from *somewhere*, i.e., is never created or destroyed which reflects a qualitative notion of energy conservation.

Table 1  
*Overview of systems, energy, and fields ideas as well as key phenomena as they are introduced across the learning sets.*

Learning Set	Systems Ideas	Energy Ideas	Fields Ideas	Phenomena
1	Objects can work together to accomplish a task. We can think of a device as one system or smaller (sub)systems working together.	When an object starts moving, energy is transferred to it When an object heats up, energy is transferred to it. Energy can be transferred via heat or light.	NA	Rube Goldberg machine Radiometer Hero's engine
2	We can think of an object as a system of particles.	Temperature increases as random particle motion increases. Energy transferred to a system must come from another system, and vice versa.	NA	Hot/cold knives Conduction simulation Colliding carts
3	A system can be made of a collection of objects and a field.	NA	Objects can push or pull at a distance via fields. Energy transfers to/from the fields between objects when the distance between them changes.	Repelling magnets Pendulum Bouncing ball
4	It is often useful to distinguish between the system of interest and the surroundings.	Energy tends to spread to as large of a system as possible. A system with only energy transfers out of it will eventually cease to function.	NA	Bounce/no-bounce" balls Sliding vs. rolling down a ramp Battery-powered pendulum with no battery

**LS 3: ENERGY TRANSFERS TO AND FROM FIELDS.** This learning set introduces the idea of energy transfers to and from fields to interpret phenomena that involve interactions at a distance, such as gravitational and magnetic interactions. In an investigation using iron fillings or a ferro fluid, students learn that the magnetic field changes its shape when magnets interact at a distance. The investigation establishes that objects interact at a distance via fields and that the shape of those fields changes as objects interact. To establish the connection between fields and energy, two magnetic carts are held together and then released. Students then model this phenomenon using the ETM. They quickly realize that they miss a system that transfers energy to the carts as they speed up. The magnetic field addresses students' need to know what the missing system is and where the energy is coming from. This episode is not only an example of how energy is presented as a useful idea that helps to gain new insight into phenomena in the systems-transfer unit, but also shows how fields are introduced in a substantially different way than in traditional instruction: Fields are not introduced as a mathematical abstraction, but as a concept that fills a conceptual void. In their ETMs, students represent fields as boxes like any other system (Figure 2).

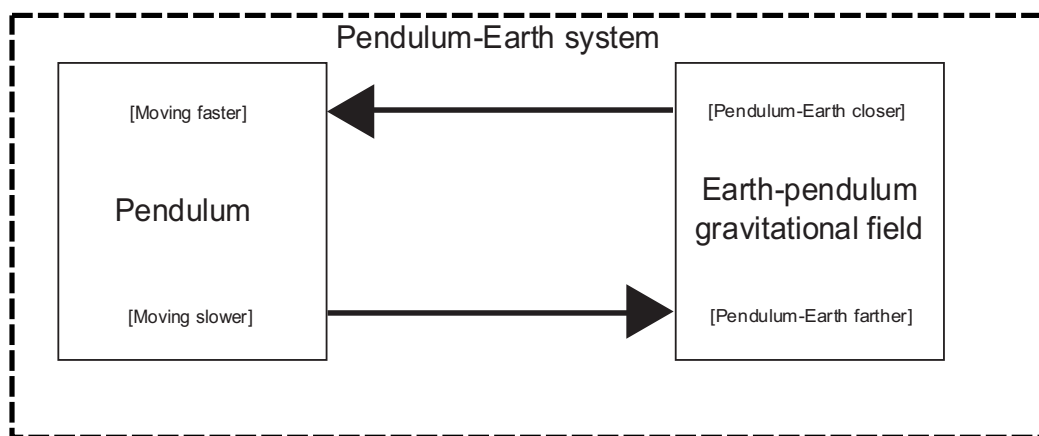


Figure 2. ETM for a frictionless pendulum. The dashed line represents the boundary of the system.

In the 2017 enactment, fields between macroscopic objects (magnetic & gravitational field) and fields between particles (electric fields between

atoms or molecules) where introduced. In the 2018 enactment, only fields between macroscopic objects were included.

**LS 4: MODELLING COMPLEX PHENOMENA AND CONTINUING PROCESSES.** The last learning set explores energy transfers in more complex phenomena that include continuing processes. Students learn to extend the Energy Transfer Model to account for relative rates of energy transfer (e.g., in a pendulum that dissipates some of its energy to the surroundings while getting slower). In their ETMs, students mark these differences via varying arrow width (see Figure 3). This allows students to go back at the driving question and explain that some things keep going as there are balanced energy transfers into and out of the observed system (e.g., electricity being supplied at the same rate to the system of an ideal pendulum as heat is being dissipated from the system to the surroundings) and things stop because energy is dissipated out of the system of interest into the environment.

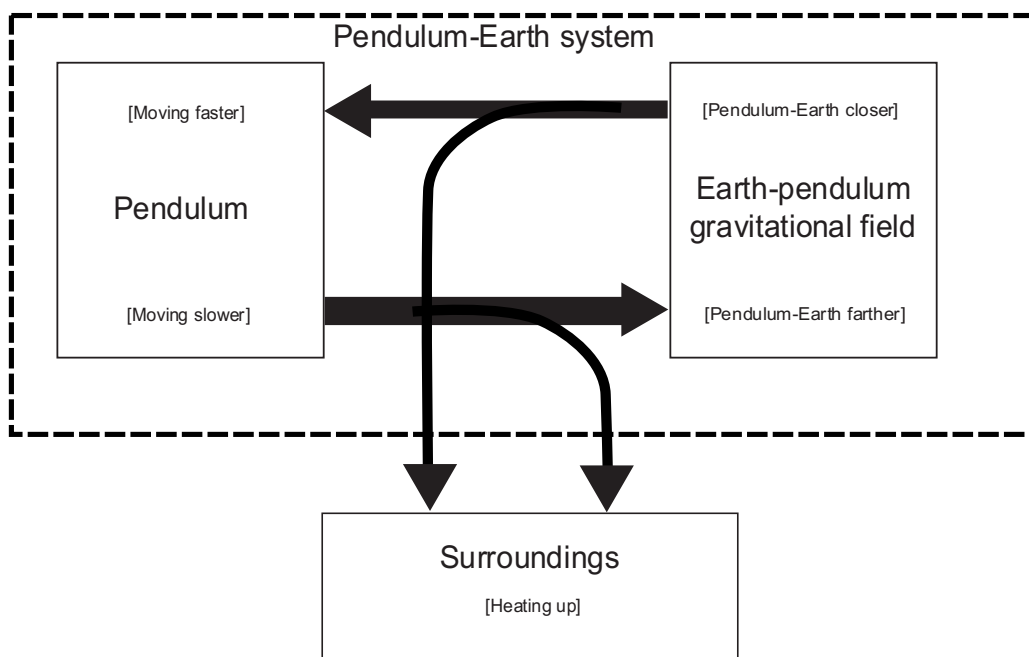


Figure 3. ETM for a pendulum swinging in air. Arrow thickness represents relative rates of energy flow.

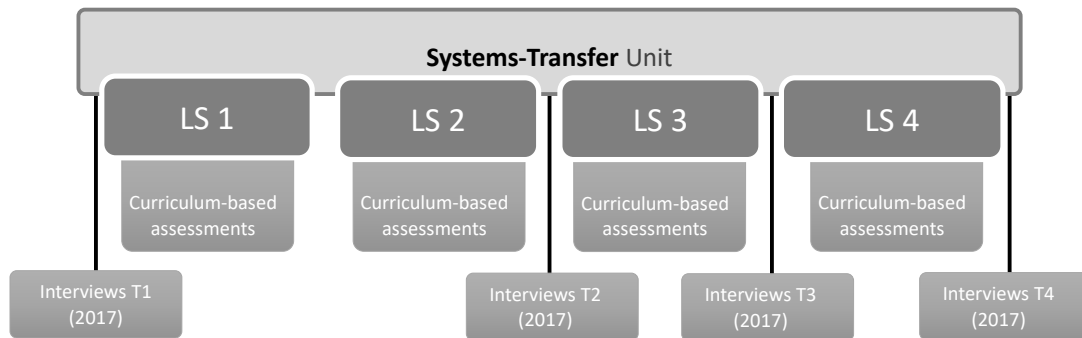
## METHODS

### UNIT ENACTMENTS AND SAMPLE

We draw on data from two consecutive enactments of the systems-transfer energy unit in 2017 and 2018. The 10-week unit was designed as a replacement for the 7th grade energy unit in the INVESTIGATE curriculum that the participating schools employ. Therefore, all students entered the study after similar curricular experiences and in the first half of 7th grade. To enable a fair comparison between the 2017 and 2018 enactment, we focused on data from the class-rooms of the two teachers that participated in both enactments. Those teachers taught the unit in a midwestern, rural school to 181 students in 2017 and 191 students in 2019. The teachers received four days of professional training concerning the systems-transfer approach before/during each enactment.

### DESIGN AND INSTRUMENTS

Figure 4 gives an overview of the overall design and assessments used.



*Figure 4.* Overall design and data sources of the 2017 and 2018 enactments. If not specifically noted, data was collected in both enactments.

**CURRICULUM-BASED ASSESSMENTS.** The curriculum-based assessments were developed following a refined version of the procedure by Harris et al. (2016) that synthesizes evidence-centered design (Mislevy & Haertel, 2007) and construct-mapping (Wilson, 2005). The resulting tasks targeted learning

goals from the four learnings sets in the unit (modeling interactions between systems, modeling balanced processes, energy transfers to and from fields, modeling complex phenomena and continuing processes) and require students to blend disciplinary knowledge, science practices, and cross-cutting concepts, i.e., knowledge-in-use (Harris et al., 2016).

The tasks mostly emphasized the scientific practices of modeling and explanations. To avoid assessing rote learning, the tasks did not use the same phenomena as in the unit, but similar ones (e.g., in a phenomenon in which light makes an object move, the unit featured a radiometer, whereas the curriculum-based tasks featured a solar car). Four tasks were administered after each of the four lesson sets. For an example of the tasks and the respective scoring rubric, see online supplement S1.

The tasks were scored by experienced scorers who were trained by the researchers. All student responses were mixed so that scorers could not tell to which measurement timepoint the student answer belonged. 10% of the student answers were scored by a second rater. We found satisfactory inter-rater agreement (mean = 84%, SD = 10%).

**INTERVIEWS.** Our research and development work follows the principles of project-based learning, including its goals to achieve coherent teaching and cumulative learning. Accordingly, we aimed to describe how students' ability to use energy ideas and related concepts from the systems-transfer unit to explain phenomena would develop across the unit. To gain deeper insight into students' thinking that goes beyond what the written assessments reveal, we conducted interviews.

A subsample of  $N = 30$  students from the 2017 enactment were asked by the teachers to participate in an interview study stretching four interview timepoints across the systems-transfer unit (in the following: T1-T4): just before the unit (T1), after LS 2 (T2), LS3 (T3), as well as shortly after the end of the unit (T4). Out of the 232 students participating in the unit in the 2017 enactment, the participating teachers selected two to three interviewees from

each of their classes, based on a request from the researchers to identify a sample of students who they felt would be comfortable being interviewed and who represented a range of student abilities in their classes. All interviews were conducted by the authors of this article. Based on their total score on the curriculum-based tasks, the interview sample is representative for the sample as a whole ( $t(230) = 0.20, p = .84, d = 0.04$ ).



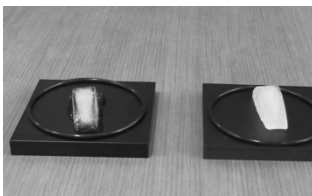
At each of T1-T4, students were interviewed according to a structured interview protocol, following an adapted version of the interviews-about-instances method (Osborne & Gilbert, 1980). In this protocol, students were shown short videos (ca. 10s, see online supplement S2) of a series of phenomena and asked "How would you explain this phenomenon?". Students were not specifically asked to use energy ideas or other concepts from the unit to make sense of the phenomenon. After students' initial response, non-instructional follow-up questions using the language of the student were used to clarify ambiguous or unclear student statements. The interviewers were instructed not to use directional prompts, directional feedback, or conceptual clarification questions. If interviewers accidentally used any of these, the respective sections of the interviews were not considered for analysis.

We focus our analysis on the three phenomena shown in Table 2 – bouncing ball, melting ice, spinning cup. All phenomena were familiar to the students as they were addressed in the unit at some point. Further, we used a simplified version of the bouncing ball that only shows how the ball falls but not how it bounces at T2 and T3.

The bouncing ball and falling ball allow us to track how students use energy, systems, and fields ideas in a phenomenon that involves interaction-at-a distance on the macroscopic scale throughout the unit. Previously, approaches that emphasized transfer either used forms in such phenomena or avoided them (Millar, 2011; Papadouris & Constantinou, 2016).

Bouncing ball, melting ice, and spinning cup helps us to see how students use energy, systems, and fields ideas in phenomena that involve dissipation, e.g., as the ball bounces lower, and whether they address microscopic fields, e.g., as the ball deforms. Phenomena that involve dissipation are interesting because students in forms-based approaches are known to struggle with conservation in dissipative phenomena (Daane, McKagan, Vokos, & Scherr, 2015), whereas the systems-transfer perspective should support students in developing a conservation idea. We focus on differences between macroscopic and microscopic fields because students in middle school are known to struggle with the particulate nature of matter (Novick & Nussbaum, 1981) and thus microscopic fields may be more difficult than macroscopic ones.

Table 2  
*Overview of phenomena in the interviews-about-instances at the different measurement time points. Reference explanations for these phenomena, as well as the respective videos can be found in online supplement S2.*

Measurement point	Phenomenon and explanation	Sample picture
T1, T2, T3, T4	<p><b>Bouncing ball.</b> A basketball is being let go by a person, drops to the ground and then rebounds until it stops.</p> <p><i>Note:</i> At T2 and T3, students only saw the ball's decent until it hit the ground, but not the rebounding process.</p> <p>Phenomenon addressed in the curriculum before T3.</p>	
T1, T4	<p><b>Spinning cup.</b> A paper cup with tilted ventilation slits is suspended upside-down over a small sterno candle. As the warm air over the candle rises, the cup starts spinning.</p> <p>Phenomenon addressed in the curriculum before T3.</p>	
T1, T4	<p><b>Melting ice cubes.</b> Two similar ice cubes are each placed on a plate, the latter of which being identical in temperature, size, and color. Unbeknownst to the interviewee (at T1), one is made of high-density foam the other of aluminum.</p> <p>Phenomenon addressed in the curriculum before T4.</p>	



**ANALYSES**

In answering our research question “How does students’ usage of systems, transfer, and fields develop over the course of the systems-transfer unit?” we draw on the curriculum-based assessments to provide a broad quantitative picture of how successfully students use systems, transfer, and fields ideas throughout the unit. To be able to compare across lessons sets, we calculated the percentage of the maximum possible score for each curriculum-based assessment. Given that introducing fields and systems – two ideas that are considered challenging – may put an additional burden on lower achieving students, we split the sample into three groups of differently achieving students and drew on the written assessments to investigate for such effects. We split the sample based on their average grade across mathematics, science, and English as a proximal measure for general achievement: low achieving students with a grade average below the 25th percentile, high achieving students with an average grade above the 75th percentile, and medium achieving students whose grade was between the 25th and 75th percentile. Further, we compared how the three groups of differently achieving students performed on curriculum-based tasks that included fields and tasks that did not include fields (see online supplement S1 for an example of a fields and non-fields task). For fields-related tasks, we drew on tasks from LS 3, where fields were introduced. For non-fields tasks, we drew on tasks from LS 2. For both learning sets, the scientific practices emphasized in the assessments were identical and balanced (using models, constructing explanations).

In all analyses where we compared across enactments, we performed propensity score matching (Rosenbaum & Rubin, 1983) based on students’ average grades across mathematics, science, and English to adjust for differences in general student achievement between the students that participated in the two enactments. The matching process provides us with subset of 132 students from each enactment that have nearly identical distributions in their average grade.

To compliment these analyses, we used the interview data to provide a in depth perspective. We analyzed a total of  $N = 176$  explanations of the three phenomena described above, using qualitative content analysis (Mayring, 2014). We employed a mixed approach of deductive and inductive elements: First, top-level categories were derived theoretically that describe central elements with regards to the unit. We then used a total of 660 units of analysis, each representing a single idea or type of explanation that the student expressed to inductively formulate the categories presented in this paper. The categories fall into three broad divisions: 1) type of explanation the student employed, i.e., based on energy, other science ideas, or drawing on every-day ideas, 2) students' application and conceptualization of fields, and 3) students' use of ideas related to energy conservation and dissipation.

All coding and analyses of cross-occurrence of categories were conducted using MAXQDA 18. All categories were revised multiple times and formulated using positive and negative coding instructions, as well as anchoring examples. An interrater reliability analysis was conducted with ca. 18% of the units of analysis and two raters, showing near-perfect agreement ( $\kappa = 0.88$ , Landis & Koch, 1977). The categories shown as part of the results represent a selection but cover the vast majority (94%) of all student ideas detected in the analysis.

## RESULTS

### *USAGE OF ENERGY AND SYSTEMS IDEAS*

The relatively high scores in LS 1 and 2 (Figure 5) show that a majority of students use energy and systems ideas successfully to make sense of phenomena in a way that corresponds with a substance-like model of energy. When fields are introduced in LS 3, scores drop and remain on a similar level in LS 4.

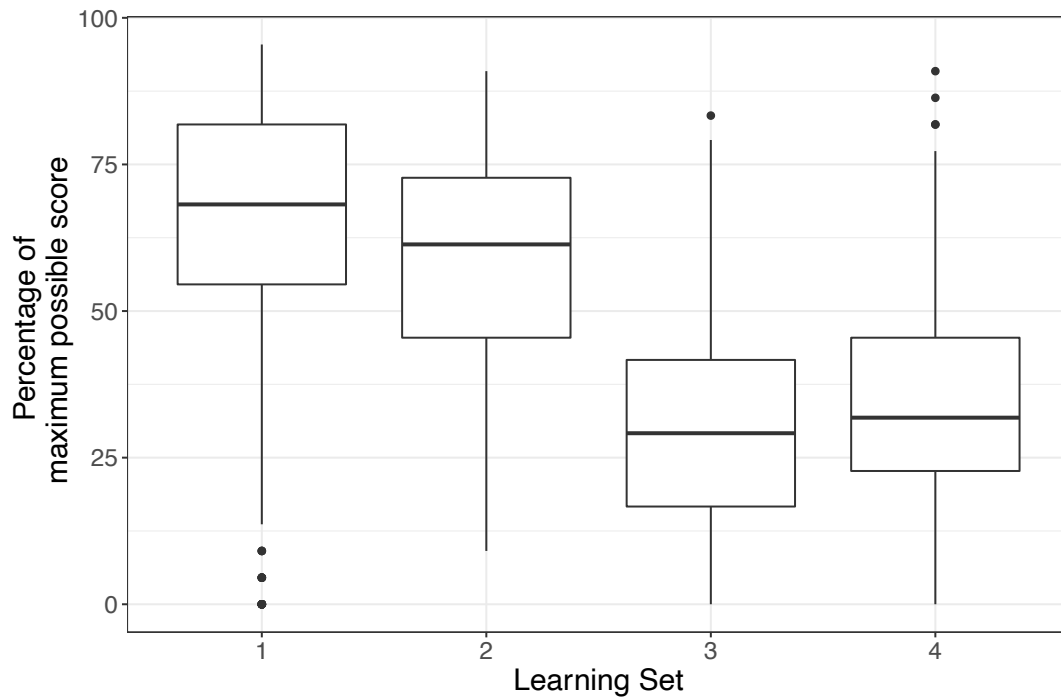


Figure 5. Boxplots (box: middle quartiles, bar: median, whiskers: extend to largest / smallest value within 1.5 times interquartile range from respective hinge) showing the percentage of maximum possible score of the curriculum-based knowledge-in-use assessments for the four learning sets pooled across both enactments.

Our interview results support the picture that students' progress towards using energy in a way that aligns with a substance-like model of energy (Figure 6). The number of students using a systems-transfer perspective continually increases from LS 1 to 4 until all students use systems and transfer ideas in LS 4. The number of students using forms ideas remains constantly low. At the end of the unit, some students use systems and transfer ideas in conjunction with forms ideas:

#### **T4, Spinning cup**

I: *So the candle is doing what?*

S: *Giving off heat energy to the cup or the air.*

The number of students that use energy ideas in a way that does neither align with a forms or systems-transfer perspective decreases from 10 students in the beginning to only 2 in the end.

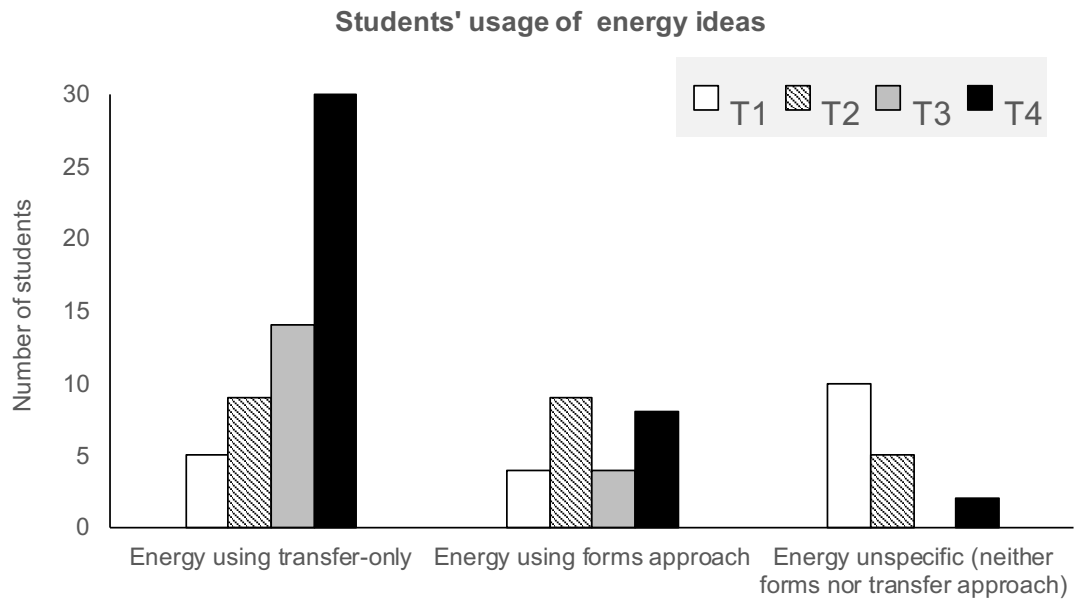


Figure 6. Energy ideas from the systems-transfer unit as used in students' explanations across the unit.

In addition to students using a systems-transfer perspective more and more over the course of the unit, Figure 7 shows students activating other science ideas, such as force, heat or gravity less and less (*"The girl or man is dropping the ball and gravity pulls things down towards the earth"*). This indicates that students use an increasingly focused set of systems, energy, and fields ideas to make sense of phenomena.

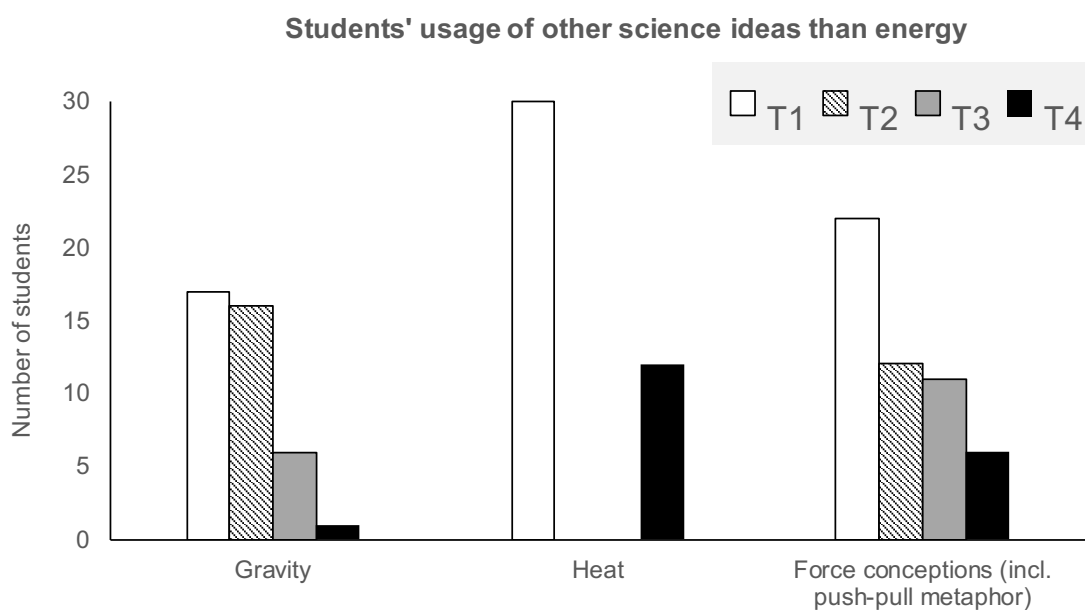


Figure 7. Other science ideas than energy as used in students' explanations across the unit.

When students use the systems-transfer perspective at the end of the unit, the majority of interviewed students (24 out of 30) tracked energy transfers correctly across systems, always locating energy somewhere and in line with a qualitative notion of energy conservation. While some students used language such as "energy loss" they were able to elaborate on these instances, indicating to what system the energy was "lost".

**T4, Melting ice**

S: *And I know one of the blocks is made of metal, one's made of plastic.*

I: *Okay, can you figure it out by thinking about which one is which?*

S: *I'm pretty sure the one that melts faster is the metal one. [...] Because the metal, the metal like, is really cold. And so it gives off - I don't know. It gives off energy to the bigger surroundings and it makes the ice cube hotter as it's melting.*

**T4, Bouncing ball**

S: *Well once he lets go of it, it's [the ball] hitting the air molecules in the air and that's kind of the reason it gets slower. Like, it doesn't bounce as high and when it hits, like, the ground, it transfers the energy to the ground and then, every time it does that, it loses like a little bit of energy.*

I: *[...]. I'd be interested: what's exactly happening to the energy when the ball hits the ground?*

S: *Well it's transferred to the ground and then, since the ground is, like, in contact with the air molecules, it transfers to those [...].*

Lastly, Figure 8 shows that in both enactments, high achieving students performed continually better than medium achieving students across the four learning sets and that medium achieving students perform continually better than low achieving students. The difference between high, medium, and low achieving students stays relatively constant across the four learning sets. A two-way repeated measures analysis of variance supports this result, as main effects for learning set ( $F(3,648) = 229.15, p < .001$ ) and achievement ( $F(2, 250) = 50.39, p < .001$ ) were statistically significant, whereas we found no evidence for an interaction between learning set and achievement ( $F(6, 648) = 0.82, p > .05$ ).

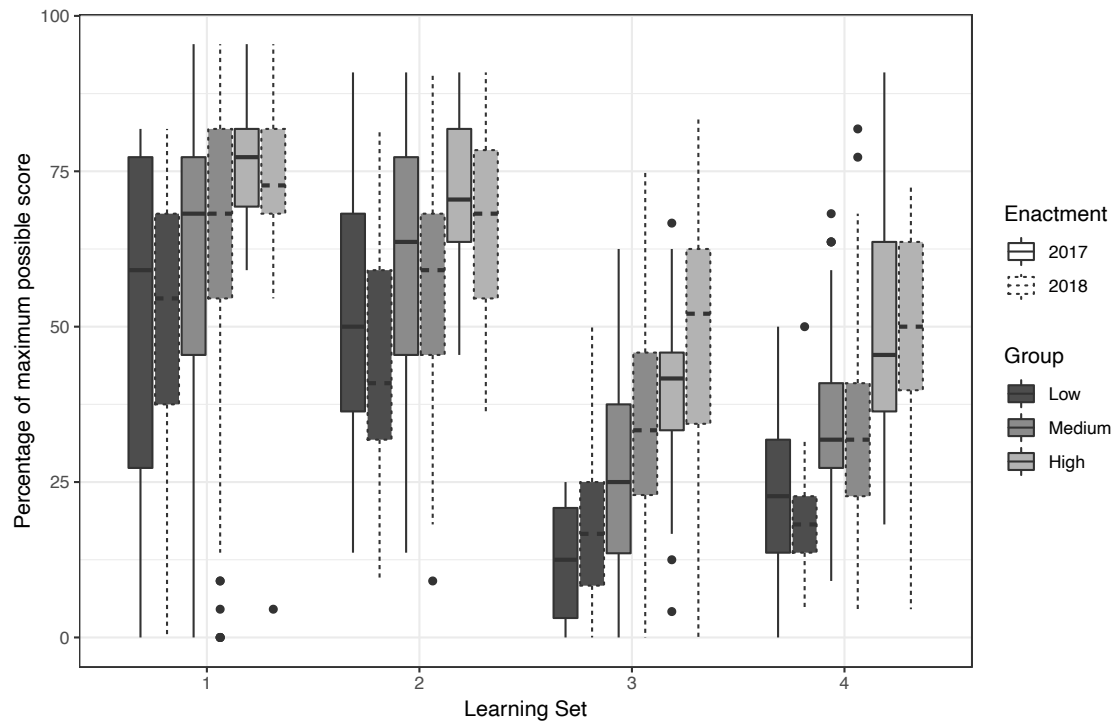


Figure 8. Boxplots showing percentage of maximum possible score of the curriculum-based knowledge-in-use assessments for the four learning sets in the matched samples from the 2017 and 2018 enactment. Split across low, medium, and high achieving students.

### USAGE OF FIELDS IDEAS

The step decrease in students' scores in the LS 3 curriculum-based assessments (Figure 5) indicated that fields are challenging. However, as Figure 9 shows, fields do not put an additional burden on low achieving students or provide additional benefit for high achieving students, i.e., there is no statistically significant difference between fields and non-fields tasks for any of the different achievement levels. While the 2017 results indicate that low achieving students performed slightly better on non-fields than on fields tasks, this effect is not statistically significant. Further, averaging across both enactments leads to no statistically significant difference ( $t(43) = 1.52, p = .14, d = 0.27, 95\% \text{ CI } [-0.14; 0.69]$ ).

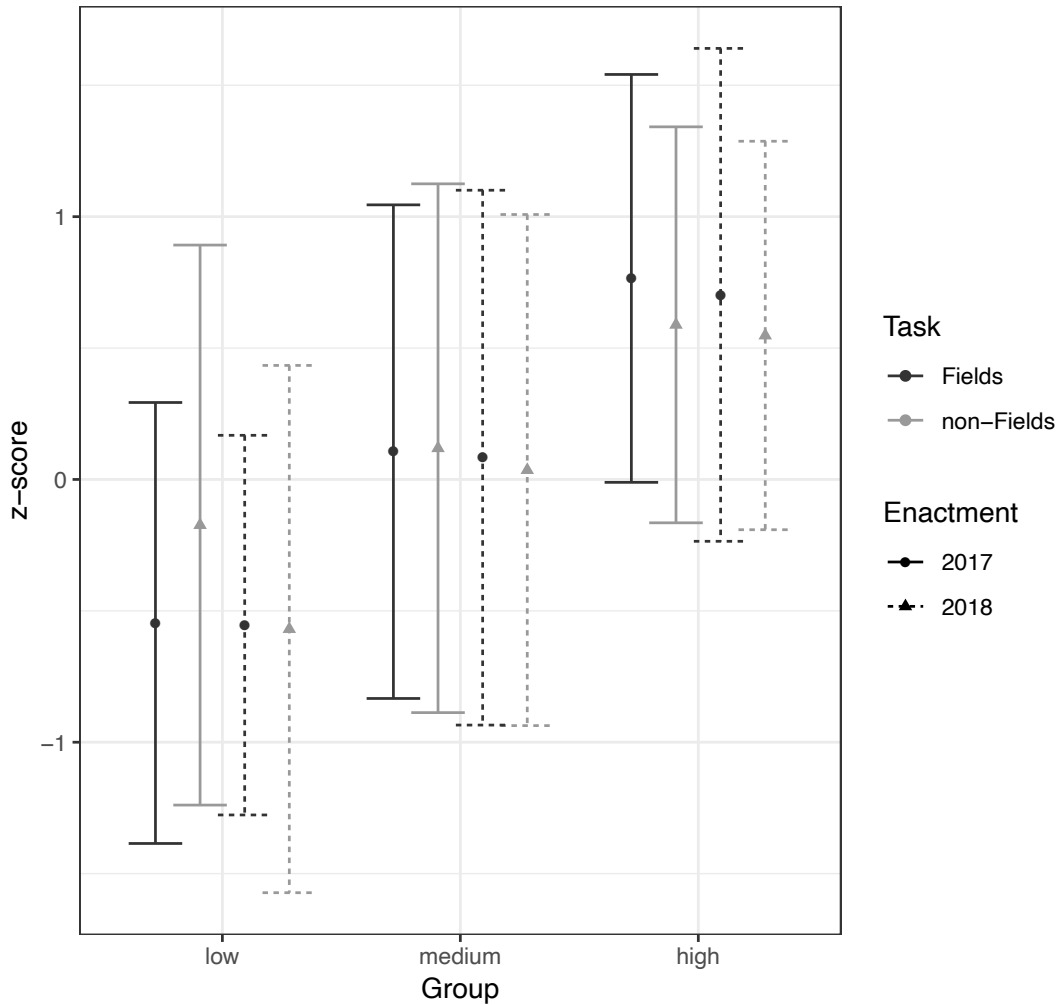


Figure 9. Mean and standard deviation for fields and non-fields tasks for low, medium, and high achieving students across both enactments.

Our interview analysis supports that students struggle with fields but also shows that after fields were introduced in LS 3, two thirds of students use fields ideas at T3 and T4 while at the same time relying less and less on the idea of gravity to make sense of the falling ball (Figure 7). A more detailed analysis of students use of fields ideas shows that around one third of students talks about fields as stores of energy (*"Energy is stored in the gravitational field, so that when you release it [the ball], it transfers from the gravitational field to the ball"*), about one quarter about fields as mediating interaction at a distance (*"Well like the gravitational field pulls it downward."*), and another third talk about fields in both ways (Figure 10).

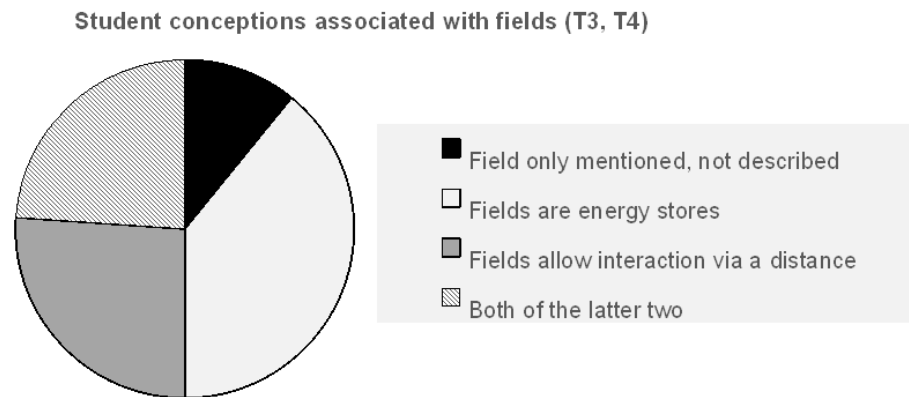


Figure 10. Shares of conceptions associated with fields. Data pooled across T3 and T4, as it is almost identically distributed.

We found students' struggles with fields to be tied to identifying the correct processes associated with the field and the correct direction of energy transfer. In several cases, it was hard to judge how they understood the function of fields in the occurring processes, as the students appeared to know a field was involved, but associated energy transfers to / from that field to an unfitting process:

#### T4, Bouncing ball

I: *And what happens to the ball?*

S: *It transferred energy to the gravitational field and then the gravitational field pulled it more. The gravitational field took some of its energy and [...] so it had a little left that's why it didn't bounce as high to where it was. Because some energy went into the gravitational field. And then every time it hits the ground it transfers more energy to the gravitational field and then eventually it transfers all of its energy to it and stop moving.*

#### T4, Bouncing ball

S: *The energy is going from the ball to the pavement and from the pavement to the gravitational field.*

I: *Where's the gravitational field?*

S: *In the air. It's like everywhere.*

This difficulty can be conceptualized in two ways: First, students appear to mix up fields and related systems within a chain of energy transfers. Second, when they use the term field, it appears to be a receptacle for energy that is currently not clearly observable, without need to focus more closely on how energy is stored in and given of from the field (e.g., by a stretch in



the fields between atoms). A subsequent in-depth analysis of a fields task in the curriculum-based tasks where students had to identify the systems, processes, and transfers involved in soccer juggling, an activity where one tries to keep a soccer ball in the air by kicking it repeatedly (see online supplement S1), reveals a similar picture. Students' scores on identifying the involved systems (the soccer ball and the ball/Earth gravitational field) are significantly higher than students' scores on identifying the respective processes ( $t(263) = 12.55, p < .001, d = 0.58$ ) and the direction of energy transfer ( $t(263) = 9.77, p < .001, d = 0.46$ ).

Further, we found only few students using microscopic fields in the interview, e.g., to describe how the ball bounces. Figure 11 shows a subsequent comparison between students' scores on LS 3, which focused on fields, in the 2017 and 2018 enactments. It reveals, that students scored significantly higher in the 2018 enactment where only macroscopic fields were addressed than in the 2017 enactment where microscopic and macroscopic fields were addressed ( $t(232) = 3.54, p < .001, d = 0.46$ ).

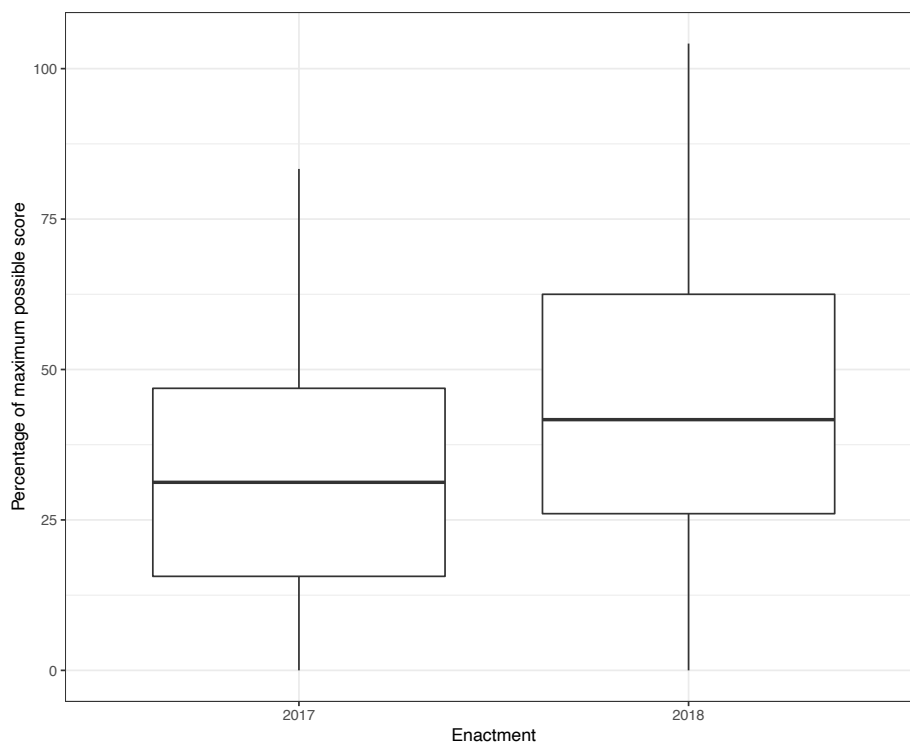


Figure 11. Boxplots of the curriculum-based knowledge-in-use assessments for learning set 3 for the 2017 and 2018 enactment.

Lastly, we note that although students struggled with fields, they continued to account for energy, i.e., there were no explanations in which energy simply appeared or disappeared.

## **DISCUSSION**

A unitary approach to teaching energy requires to address energy, systems, and fields – three complex ideas and each challenging on its own. We approached this challenge by drawing on two principles: 1) modest goals, i.e., we only introduced the absolutely necessary components of each of these ideas, and 2) introducing new concepts so that they answer a need-to-know.

Over the course of the unit, students started to use systems, energy, and fields ideas in a way that aligns with a substance-like model of energy. In line with this model, most students tracked energy successfully as it was transferred between systems, exhibiting a qualitative notion of energy conservation. With respect to fields, we found macroscopic fields to be more accessible in middle school than microscopic fields. Further, students struggled with correctly determining the direction of energy transfer as well as the process related to energy transfer. Lastly, we found no evidence for an interaction between students' general achievement level and their success in using systems, transfer, and fields ideas over the course of the unit.

What do these results imply for the teaching and learning of energy? In sum, they indicate that the benefits of the unitary perspective outweigh the cost of introducing fields, adding weight to the finding of Fortus et al. (2019) that students in the systems-transfer unit outperformed students in a comparable forms-based unit with respect to their progress on the NGSS middle school performance expectations. More specifically, students high scores in the first two learning sets and respective T2 interviews as well as the T3 and T4 interviews indicate that students successfully built a substance-like model of energy and applied it without violating energy conservation, even when they struggled with fields or faced dissipative phenomena that are prone to trigger the violation of conservation (Daane et al., 2015). Given the

notorious difficulty of conservation (Herrmann-Abell & DeBoer, 2017; Liu & McKeough, 2005; Neumann et al., 2013) this finding adds important support to the theoretical arguments that support a substance-like model of energy (Brewer, 2011; Ellse, 1988; Falk et al., 1983; Scherr et al., 2012; Swackhamer, 2005) as one of its central ramifications is that it entails a qualitative notion of energy conservation and supports students in developing this idea (Kesidou & Duit, 1991).

### ***IS A SUBSTANCE-LIKE CONCEPTION PROBLEMATIC?***

Our data does not allow us to say how students conceptualize energy, i.e., whether they think of energy as a substance or just talk about energy as if it were a substance. Thinking of energy as a substance would be technically wrong and the substance-like model has been criticized for potentially building this misconception (Duit, 1987) and is not supported by data (Scherr et al., 2012). However, as Reiner, Slotta, Chi, & Resnick (2000) point out, students appear to have materialistic conception when they come to class already and do not build them in class. Further, given that Reiner, Slotta, Chi, & Resnick (2000) show that materialistic conceptions are very persistent to change and scientists regularly use materialistic models in the context of energy (Harrer, 2017), it appears more fruitful to build on these perceptions, as the related metaphors and reasoning patterns provide a valuable resource for students (diSessa, 1993; Lakoff, 1993). Emphasizing that the substance-like conception of energy is a model (Gray et al., 2019), could provide valuable opportunities to point out that energy is not a substance and at the same time allows to discuss the applicability, usefulness, and limits of scientific models, all important aspects of the practice of scientific modelling (NGSS Lead States, 2013). In sum, it seems that a substance-like model is at least a productive stepping stone towards a full understanding of the energy concept. This begs the questions whether substance-like models can also be helpful in other areas of the sciences where they have been shunned.

***ARE FIELDS APPROPRIATE FOR INCLUSION IN MIDDLE SCHOOL ENERGY INSTRUCTION?***

Besides the controversy about a substance-like notion of energy, interaction-at-a distance has been considered a potentially problematic aspect for unitary approaches to teaching energy. In the past, approaches that emphasized systems and transfers, either avoided (Papadouris & Constantinou, 2016) such phenomena or reverted to forms (Lehavi & Eylon, 2018; Millar, 2011). Following Swackhamer (2005) the systems-transfer unit introduced fields to apply the unitary approach consistently in phenomena that involve interactions-at-a-distance. Students, even at the undergraduate level, are known to struggle with fields, when they are introduced as mathematical abstractions in the context of forces (Furio & Guisasola, 1998). Our results provide a first impression of what students can achieve when fields are introduced in the context of energy. The high number of students activating fields ideas in the context of a falling ball, a phenomenon that neither (Papadouris & Constantinou, 2016) nor (Millar, 2011) would discuss without forms, indicate that the ideas that students need in the systems-transfer approach, fields are entities in space that mediate interaction-at-a-distance to which energy can be transferred to or from, are accessible to middle school students. This extends research that found that the idea that fields are entities in space that mediate interaction-at-a-distance is accessible in middle school (Atkin & Karpus, 1962; Bar et al., 2007; Bradamante & Viennot, 2007). However, we also found a potential limit of fields ideas that are accessible in middle school, as students struggled to use microscopic fields idea and rarely activated them in the interviews. On one side, this may attributed to middle school students generally struggling with particle ideas (Novick & Nussbaum, 1981). On the other side, potential reason might be that macroscopic fields answered a strong need-to-know (Krajcik & Shin, 2014) for students but microscopic fields did not to the same extent, because microscopic fields are only needed to explain how a change in shape or structure of macroscopic objects can store or release energy.

***DOES A SYSTEMS-TRANSFER APPROACH FAVOR ALREADY HIGH-ACHIEVING STUDENTS?***

A last potentially problem with emphasizing systems, transfer, and fields was the possibility that the approach may benefit high achieving students more than low achieving students. Similar effects are well known as aptitude treatment effects in the educational literature, for example high achieving students profit open learning environments whereas low achieving students profit from additional guidance (Cronbach & Snow, 1977). With respect to energy, Bächtold & Munier (2018) recently voiced the concern that historical texts in their instructional approach seemed to be off little effects because they benefitted high achieving students but put an additional burden on lower achieving students, effectively averaging the observed effect to nil. However, they had no data to provide evidence for either possibility. In our study we found no evidence for such effects. A limitation to this finding comes from our sample size as it limits the size of effects we would have been able to detect, thus we cannot fully rule out that small aptitude treatment effects with respect to achievement exist.

***AN ALTERNATE PATHWAY TO DEVELOPING CONSERVATION IDEAS?***

Finally, our results show that energy learning progression do not have to go through forms as the existing energy learning progressions literature may suggest (Herrmann-Abell & DeBoer, 2017; Liu & McKeough, 2005; Neumann et al., 2013) and scholars have argued (Doménech et al., 2007; Duit, 1984). This extends earlier findings of students in elementary school successfully building an understanding of energy without relying on forms but focusing on transfers between systems (Lacy, Tobin, Wiser, & Crissman, 2014). At the same time it highlights a common criticism of learning progressions research that does not have an instructional components, i.e., the effective filtering of everything but the dominant instructional approach and developmental patterns that may hide (Duncan & Hmelo-Silver, 2009; Duncan & Rivet, 2013). Lastly, it opens the question of how an alternative learning progression around the idea of transfer might look for the high school level.

**IMPLICATIONS**

In this paper, we argue and present evidence that concepts which have long been avoided in middle school energy instruction may have instructional value, as long as instruction related to these concepts addresses only necessary ideas. Further, we provide evidence that an idea which some regard as a “misconception” or “alternative framework” (e.g., Watts, 1983) – the substance-like conception of energy – may in fact be productive in developing more sophisticated ideas about energy. More generally, one might ask what other potential misconceptions can have value as productive stepping stones, given that we emphasize that they are models and thusly discuss their limits and applicability? For example, science educators often have few reservations teaching the matter concept using a sequence of historical atomic models. Although the intermediary models are to be later replaced by more sophisticated ones, they are productive when they are introduced and serve as stepping stones in building the full and complex model over time. Further, doing so presents opportunities to integrate disciplinary knowledge with the scientific practice of modeling in the sense of the vision of knowledge-in-use (Harris et al., 2016) and three-dimensional learning presented in the Framework for K-12 Science Education (National Research Council, 2012).

We introduced fields as being real entities (as opposed to mathematical abstractions) and purposeful as they addressed a need-to-know of students. From our data we cannot tell which of these two elements helped students to learn about them but as fields are an important concept in other domains of physics and the sciences as well, e.g., the velocity field in hydrodynamics, it appears warranted to address this question in the future.

Lastly, seeing students succeed in using systems, energy, and fields ideas to make sense of a falling ball should remind us not to underestimate what students can achieve and not to shy away from complex ideas too quickly. Complex ideas have to be built over time, beginning with simple constituents. As experts we may struggle to see these, as terms like “system” or “field” invoke the full complexity of these concepts. However, when we

consider what modest goals might be, e.g., for learning about fields, we might find them to be quite accessible for students and laying important foundations to develop the full concept later one. This begs the question what other ideas that are typically considered too complex may very well be successfully introduced when one focuses on modest goals.

### **FUTURE DIRECTIONS**

This study, together with existing empirical studies (Fortus et al., 2019; Kubsch, Nordine, Neumann, Fortus, & Krajcik, 2019) support the case for unitary approaches for developing a qualitative understanding of energy in middle school. However, at some point, students will encounter forms-based instruction, be it in high school, college, or informal/non-formal learning opportunities. Thus, the extent to which students can make sense of forms ideas once they encounter them, will be an important question for future research. Similarly, future work may address how to progress towards a quantitative perspective that emphasizes the unitary nature of energy.

In addition, students do not only encounter energy ideas in a physical science context but also in biological or geo science. Nordine et al. (2019) have argued that the focus on systems and transfers in the systems-transfer unit aligns more closely with how energy is presented in those sciences than the traditional forms-based approach. Thus, integrated in a larger coherent curriculum, the systems-transfer unit may contribute to future learning across disciplinary borders to a greater degree than a traditional forms-based unit (Fortus, Sutherland Adams, Krajcik, & Reiser, 2015).

Finally, this study as well as other research on the systems-transfer approach (Fortus et al., 2019; Kubsch, Nordine, Neumann, Fortus, & Krajcik, 2019) has focused on cognitive measures. Thus, affective and motivational benefits or drawbacks of the approach remain to be researched in future studies.

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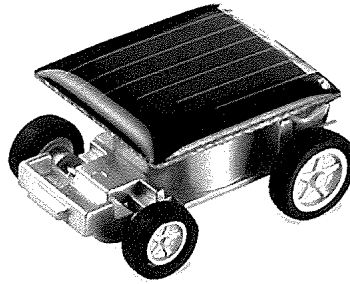
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**ONLINE SUPPLEMENT S1**

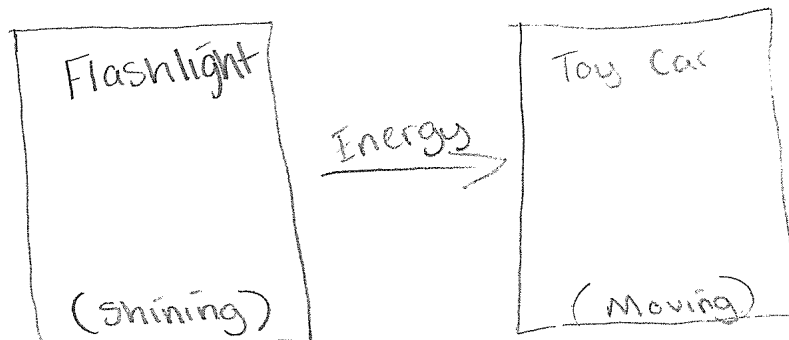
**EXAMPLE TASK AND RUBRIC FROM LEARNING SET 1**

**SOLAR CAR TASK FROM LEARNING SET 1**

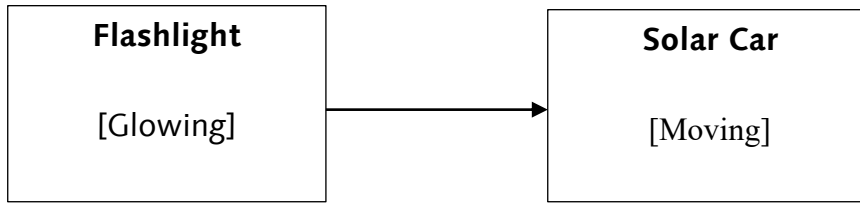
Below you see a picture of a little toy car. When you point a flashlight at the car, it starts to move.



Draw a model which describes how energy involved in making the car move.



**SCORING RUBRIC FOR SOLAR CAR TASK IN FIGURE 1.**



Scoring	0	1	2
Representation of the energy related systems components and the systems borders	<p><b>Students don't/incorrectly identify and describe the relevant system components or borders</b></p> <p>The system doesn't include both flashlight and solar car</p>	<p><b>Students incompletely identify and describe the relevant system components or borders</b></p> <p>Student presents either One of the systems above OR Both systems above and an irrelevant system OR One of the systems above and an irrelevant system</p>	<p><b>Students identify and describe the relevant system components and borders</b></p> <p>Student presents the two systems above</p>
Representation of the energy related processes in systems	<p><b>Students don't/incorrectly identify and describe the relevant energy related processes in systems</b></p> <p>No reference to flashlight glowing or the solar car moving</p>	<p><b>Students incompletely identify and describe the relevant energy related processes in systems</b></p> <p>One process (glowing or moving) is correct and the other is incorrect or missing.</p>	<p><b>Students identify and describe the relevant energy related processes in systems</b></p> <p>The flashlight is listed as glowing and the solar car as moving.</p>
Representation of energy transfer mechanism linking the systems components	<p><b>Students don't/incorrectly identify and describe the relevant energy transfer mechanism linking the systems components</b></p> <p>No arrow is drawn.</p>	<p><b>Students incompletely identify and describe the relevant energy transfer mechanism linking the systems</b></p> <p>The arrow suggesting energy transfer is presented and pointing to a correct system OR coming from a correct system</p>	<p><b>Students identify and describe the relevant energy transfer mechanism linking the systems</b></p> <p>The arrow suggesting energy transfer is presented and pointing to a correct system AND coming from a correct system</p>

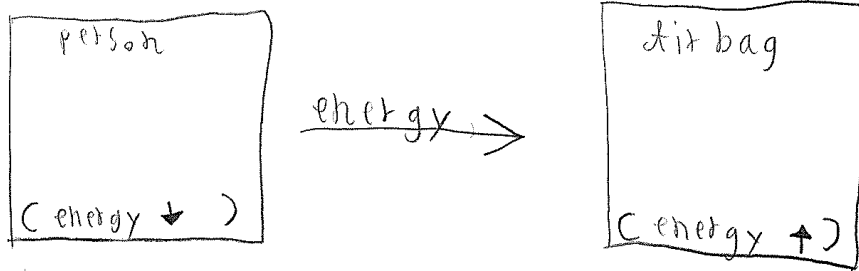
**EXAMPLE NON-FIELDS AND FIELDS TASK**

**NON-FIELDS TASK**

A car airbag is an air-filled cushion with special vents that allow air to escape. In a crash, the airbag inflates quickly. When the person's head collides with the bag, air is pushed out of the vents.



Draw a model which describes how energy is involved when someone's head collides with an airbag.



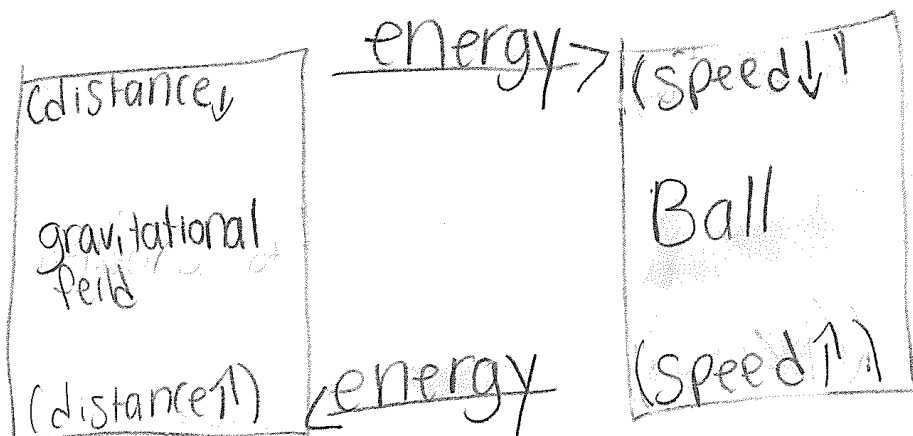


**FIELDS TASK**

The soccer player below is "juggling" by kicking the ball in the air as many times in a row as he can (see picture).



Draw a model which describes the energy transfers that occur when the ball rises (starting just after the player kicks it) and falls again (ending just before it hits the player's foot again).





**PUBLICATION II:  
SUPPORTING STUDENTS IN USING ENERGY IDEAS TO INTERPRET  
PHENOMENA: THE ROLE OF AN ENERGY REPRESENTATION**

**ABSTRACT**

In the sciences, energy is an important idea to get insight into phenomena, as energy can help to reveal hidden systems and processes. However, students commonly struggle to use energy ideas to interpret and explain phenomena. To support students in using energy ideas to interpret and explain phenomena, a range of different graphical representations are commonly used. However, there is little empirical research regarding whether and how these representations actually support students' ability to use energy ideas. Building on common ways of representing energy transfer, we address this issue by exploring whether, and if so how, a specific representation called the Energy Transfer Model (ETM) supports middle school students' interpretation of phenomena using the idea of energy transfer. We conducted an interview study with  $N = 30$  8<sup>th</sup> grade students in a quasi-experimental setting and used qualitative content analysis to investigate student answers. We found evidence that students who construct an ETM when making sense of phenomena consider the role of energy transfers between systems more comprehensively, i.e., they reason about hidden processes and systems to a larger extent than students who do not construct an ETM.

## INTRODUCTION

Graphical representations are commonly used to support students in learning about energy. Those representations are designed to be actively constructed by students to support their reasoning and as anchors for collaborative sensemaking (e.g. Scherr et al., 2016). In contrast to other central science ideas such as force, there is no consensus representation for energy and there is little empirical research regarding the actual effectiveness of energy representations in supporting students. While existing representations of energy often emphasize energy as manifest in different forms (Gray, Wittmann, Vokos, & Scherr, 2019), researchers have repeatedly questioned whether forms-based energy instruction is responsible for students' difficulties with energy (Brewe, 2011; Quinn, 2014; Swackhamer, 2005). We investigated whether, and if so how, a specific representation – the Energy Transfer Model (ETM) – that emphasizes the unitary nature of energy instead of forms, supports middle school students in using energy ideas to make sense of phenomena in a physical science context.

## BACKGROUND

### *ENERGY AND REPRESENTATIONS*

Energy is inherently abstract as it cannot be directly observed or measured. Thus, reasoning about energy relies on conceptual models. When scientists use energy ideas to interpret phenomena, they often use representational tools such as mathematical formulas or Sankey diagrams (Ainsworth, Prain, & Tytler, 2011). When scientists construct such a representation, the specific affordances of the representation can constrain thinking and channel attention in helpful ways. For example, a falling ball can be described through the formula  $mgh = \frac{1}{2}mv^2$ . The rules of algebra constrain thinking as they only allow for specific manipulations and attention is channeled towards the variables in the formula and away from surface features such as the color of the ball. However, such expert representations are not accessible in middle school or lower grades when students lack the mathematical foundations.

Therefore, other Representations such as energy chains (Papadouris & Constantinou, 2016) or pie charts are introduced (see Gray, Wittmann, Vokos, & Scherr (2019) and Scherr, Close, McKagan, & Vokos (2012) for a review of existing energy representations).

Despite their ubiquitous usage in classrooms, energy representations are rarely a focus of empirical studies. As a result, research often shows examples of students successfully making sense of phenomena while constructing energy representations (Barth-Cohen & Wittmann, 2017; Papadouris & Constantinou, 2016; Tobin, Lacy, Crissman, & Haddad, 2018; van Heuvelen & Zou, 2001), but to what extent and how constructing these energy representation supports students' reasoning in making sense of phenomena remains largely unknown.

#### ***HOW CONSTRUCTING REPRESENTATIONS SUPPORTS REASONING***

Generally, research has found that active construction of representations supports problem solving and reasoning processes (S. Ainsworth et al., 2011; Chen, Wang, Grotzer, & Dede, 2018; Kirsh, 2009; Rumelhart & McClelland, 1986). The positive effects of constructing representations can be explained through cognitive and social mechanisms. From a cognitive perspective, active construction supports information processing, e.g., by lowering cognitive load, reordering information, or focusing attention (Mayer, 1997; Paivio, 1986; Rumelhart & McClelland, 1986). From a social perspective, active construction serves as a hub for shared cognition in collaborative learning environments and stimulates discussion and argumentation during consensus building which can drive inquiry (Barth-Cohen & Wittmann, 2017; Tobin, Lacy, Crissman, & Haddad, 2018; Vygotsky, 1978). Both the cognitive and the sociocultural perspective are embraced when we interpret representations as cognitive tools (Kirsh, 2010). Cognitive tools can be interpreted as all 'cultural tools that impose structure on the reasoning process' (Van Joolingen, 1998). To be effective their use must be carefully integrated with learning activities (Kim & Reeves, 2007).

The structure that cognitive tools impose on reasoning processes when interpreting and explaining phenomena, helps students to go beyond their current level, i.e., into what Vygotsky (1978) calls the zone of proximal development. This in turn can then set the stage for future learning, if carefully integrated with learning activities. For example, after tracking forms of energy in pie charts to describe the motion of a pendulum in a vacuum, tracking forms of energy in pie charts to describe a pendulum in air can lead to a need to account for another form of energy. This can guide further inquiry in pendulums in air and thus set the stage to learn about thermal energy and dissipation.

We consider the perspective of cognitive tools to be fruitful to investigate representations used to support students learning about energy, as representations such as energy chains or energy tracking diagrams are designed to a) be actively constructed and used in a learning environment and b) support students through cognitive mechanisms such as channeling of attention or constraints in thinking.

As the effectiveness of energy representations depends on their alignment to the learning environment (Ametller & Pintó, 2002; Gray et al., 2019; Kim & Reeves, 2007; Scherr et al., 2012), we describe the learning environment used in this study in the next section and then explain how the used energy representation aligns with it.

#### ***LEARNING ENVIRONMENT AND ENERGY REPRESENTATION USED IN THIS STUDY***

Traditionally, introductory energy instruction in middle school focuses on forms of energy and transformations between those forms. Informed by the emphasis on energy transfers between systems in leading documents such as the Framework for K-12 Science Education (National Research Council, 2012) and similar proposals in the literature (Brewer, 2011; Ellse, 1988; Swackhamer, 2005), we have developed a middle school unit that focuses on the transfer of energy between systems and conceptualizes energy as unitary, i.e., no forms of energy are introduced (for a detailed description of the

approach see Nordine et al., 2019). Following the recommendations in the Framework for K-12 Science Education (National Research Council, 2012), systems identify the part of the universe under investigation, thus systems can be single objects, fields, or collections of objects and/or fields. Fields are required in the systems-transfer approach to discuss phenomena that include interaction at a distance without resorting to transformations between energy forms (Nordine et al., 2019). In the unit, fields are not introduced as mathematical abstractions (as they typically are), but as systems that energy is transferred to or from in phenomena that involve interaction at a distance. First evidence suggests that 7<sup>th</sup> grade students use these ideas successfully (Fortus et al., 2019; Kubsch et al., 2019).

To illustrate this systems-transfer perspective, consider the description of a collision between two balls A and B: during the collision, energy is transferred from the system ball A to the system ball B. Ball A undergoes an energy decreasing processes as its speed decreases. In turn, ball B undergoes an energy increasing process as its speed increases. By definition, energy transfer is an exchange of energy across system boundaries. Thus, when one discusses the energy transfer from one ball to another, each ball is implicitly defined as a system.

The description of the colliding balls shows that the key ideas to make sense of a phenomenon from the systems-transfer perspective are systems, processes, and energy transfers. Further, a qualitative notion of energy transfer is implicit in the balanced energy related processes (one increasing and one decreasing) and the fact that energy is always located in a system, i.e., is not created or destroyed. Thus, a representation that serves as a cognitive tool in the systems-transfer unit should represent the key ideas of systems, processes, and transfers, and help to support students' reasoning processes around those ideas. None of the energy representations in the literature represent all of the ideas that are important to the systems-transfer perspective (see Gray et al., 2019; Scherr et al., 2012). Therefore, building on existing

ways to represent energy transfer, we developed a new representation called the Energy Transfer Model (ETM).

**THE ENERGY TRANSFER MODEL.** The ETM is designed to serve as a cognitive tool for supporting students in making sense of phenomena in the systems-transfer approach to teaching energy. It grows in complexity throughout the course of the unit as students encounter new energy ideas and make sense of increasingly complex phenomena. In its basic form the Energy Transfer Model (Figure 11) depicts two interacting systems (A and B) as boxes, describes the measurable energy related processes that are going on in these systems spelled out in brackets, and represents the energy transfer between the systems as an arrow pointing from one system to the other. Further, the arrow must always point from one system to another, i.e., it cannot start or end in “nowhere” and for every increasing energy process, there must be a decreasing energy process. This emphasizes the qualitative notion of energy conservation that when the energy of a system changes, there has to be another change in energy in some other system (Gray et al., 2019). Thus, the representation should provide support for reasoning through its graphical elements and via rules.

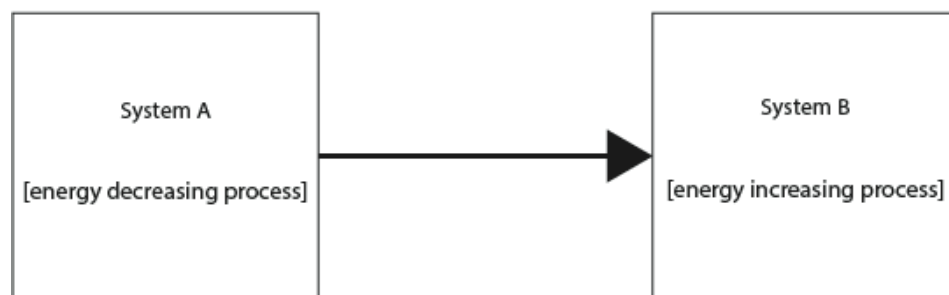


Figure 1. Base ETM.

For example, when a student has identified a system, the graphical structure of the ETM prompts the student to think about the process in that system because otherwise the process part of the representation would remain empty. Similarly, the rule that the arrow representing energy transfer always has to connect two systems, forces students that have identified one system with an energy decreasing process and an arrow pointing away from



that system, to think about what the other system to which the energy is transferred might be. By repeatedly using the base ETM to describe a wide range of phenomena, students thinking should become routinized to look for the key features of interacting systems, energy change processes happening within each system, and the direction of energy transfer between systems.

We refer to this representation as a “model” because in our curricular approach, we use this representation as part of a broader strategy to engage students in the scientific practice of modelling. In the curriculum, student initially create their own models of a phenomenon (a flashlight making a Crooke's radiometer spin), and the basic ETM is introduced through consensus-building discussions. In subsequent lessons, students use the ETM to represent key features of varied phenomena as they reason about them, and the ETM is refined and revised throughout the unit as students encounter new energy ideas and increasingly complex phenomena.

#### ***INVESTIGATING HOW CONSTRUCTING AN ETM DOES SUPPORT STUDENTS***

Despite the widespread use of pedagogical energy representation to support students, their effectiveness is seldom explicitly studied. We lack insight into the effect of constructing energy representations on how students use energy ideas and to what extent these representations guide students' reasoning in supportive ways as the perspective of cognitive tools suggests. However, this is critical when choosing or designing representations that aim at supporting students in applying energy ideas. We address this issue by asking the following research question: How does constructing an ETM support students in applying the systems-transfer perspective to interpret phenomena?

#### **METHODS**

To address our research question, we conducted an interview study during an enactment of the systems-transfer energy unit. At the point in the unit when the study took place, students had applied the systems-transfer

perspective to identify the systems, processes, and energy transfers in numerous phenomena such as collisions, melting ice, interacting magnets and constructed ETMs for these phenomena. During the interviews, all students were asked to apply the systems-transfer perspective to make sense of two phenomena from everyday life that had not been covered in the unit. Half of the students were asked to use the systems-transfer perspective by constructing an ETM (ETM group), the other half was simply asked to use the systems-transfer perspective (non-ETM group).

### ***SAMPLE***

Two teachers enacted the systems-transfer unit for 12 to 12 weeks in the 8th grade of a rural low-SES middle school located in the Midwestern United States. To avoid teacher effects, a sample of  $N = 30$  students from the teacher teaching the most students were interviewed (15% of the total number of 200 students that studied the unit). The teacher was asked to identify six students from each of her five classes who would feel comfortable being interviewed and who represented a range of student achievement levels. To investigate potential selection effects in our sample of  $N = 30$  students, we drew on pre- and post-test data originating from a larger project investigating the systems-transfer approach. We compared the gain from pre to post test of our sample of 30 students with the whole sample of 200 students that participated in the enactment of the unit. Further, we compared gain of the ETM group with gain of the non-ETM group. We found similar averages and standard deviations for the ETM and non-ETM group surmounting to a Cohen's  $d = 0.08$  ( $p = .83$ ), thus indicating no evidence for a significant difference between the ETM and non-ETM group. Concerning the difference in learning gain between our subsample and the whole sample, we find a Cohen's  $d = 0.36$  ( $p = .051$ ), suggesting a possible small difference favoring the interview sample. However, a positive selection is to be expected with students that are willing to be interviewed and is unproblematic with respect to investigating how the ETM supports students but warrants to consider this with respect to generalizing our results.

***INTERVIEW PROTOCOL***

We used a semi-structured interview protocol to ensure that all students received identical initial prompts. Students were interviewed individually. The introductory part (introduction of interviewer, consent etc.) was always the same. Then we asked the students to explain two phenomena we presented in short videos, 5-10 seconds long (videos available as online supplemental). In the first video scenario (S1), a golf ball rolls over asphalt and then stops on a small pile of sand. The sand is not visibly moving. In the second scenario (S2), a person releases a basketball from the second floor of a building and the ball falls out of the frame. One group (ETM) was prompted to construct an ETM to explain the phenomena in the videos "How could you use an energy transfer model to explain how the ball moved?". The other group (non-ETM) served as a comparison group. It was prompted to explain the phenomena using energy transfers "How could you use energy transfers to explain how the ball moved?". In both groups non-instructional prompts were used to elicit student ideas, e.g., "How do you know that energy is transferred from the ball?" after a student said that energy was transferred from the ball or "What do the boxes that you have drawn represent?" after a student drew boxes in an ETM. We set up the interview situation such that all students from both groups had access to a pen and paper which they could use to draw an ETM if they desired. Further, we did not require the students from the ETM group to draw; rather we simply asked how they could use an ETM to explain what they saw in the videos.

Interview Scenarios. In Scenario 1 (S1), a rolling golf ball comes to rest on a bed of sand. From the systems-transfer perspective, when the ball system slows down when it comes in contact with the sand, there must be an energy transfer from the ball system to another system. Since the ball slows down when it comes in contact with the sand the ball is interacting with the sand, the sand must be the second system. Since energy is transferred to the sand system, it must undergo an energy-increasing process, such as "heating up". However, such a process was not clearly visible in the video but "hidden".

Consequently, students had to infer that process. At the point in the unit when the study took place, students had learned about energy transfers in collisions between objects. However, they had not encountered "hidden" processes so far. Thus, S1 is basically a classical near (cognitive) transfer task with the added element of a "hidden" process.

In Scenario 2 (S2), a person drops a basketball which is released from rest and falls out of the frame. From the systems-transfer perspective, there are two systems involved, the ball and the Earth/Ball gravitational field. As the ball's speed increases while it is falling, energy is transferred to the ball system from the Earth/Ball gravitational field system as the distance between the ball and the Earth decreases. The study was conducted just after the students had learned about magnetic fields but before they learned about gravitational fields. Thus, students had not yet been taught that gravity is mediated by a field which functions as a system capable of energy transfer. Further, the Earth/Ball gravitational field system is not visible.

Thus, S2 is situated farther away in the students' zone of proximal development than S1. This setting allows us not only to explore to what extent the ETM supports students to make sense of a phenomenon with a "hidden" system but also to what extent the ETM helps to set the stage for future learning, i.e., to what extent can the phenomenon of the basketball speeding up without any apparent energy transfer to it, establish a need to know that the next lessons of the unit could address.

As we discussed in the background section, cognitive tools should do two things: first, support students to do better and second, generate insights that can guide further inquiry in a learning environment. The first aspect is primarily addressed by the near transfer S1 and the second by S2 which has a forward-looking component with respect to the unit.

## ANALYSIS

For the analysis of the interviews we first transcribed all audio recordings of the interviews. The students from the ETM group drew the ETMs with a smart pen. A smart pen is a pen that on top of functioning as a usual pen digitally records as a "video" what is being written or drawn with it. This allowed us to connect students' drawings with their non-ETM explanations, i.e., we know how their words correspond to their drawings.

To answer our research question "How does constructing an ETM support students in applying the systems-transfer perspective to interpret phenomena?" we first analyzed how successfully students used the systems-transfer perspective to make sense of the two scenarios. In a second step, we looked for qualitative features that revealed how students used the systems-transfer perspective when reasoning through the phenomena.

### **HOW SUCCESSFULLY DO STUDENTS APPLY THE SYSTEMS-TRANSFER PERSPECTIVE?**

We followed a deductive approach to assess to what extent students identified the elements of the systems-transfer perspective in their accounts of the phenomena. Figure 2 shows a sample answer for Scenario 1 using the systems-transfer perspective with and without an ETM.

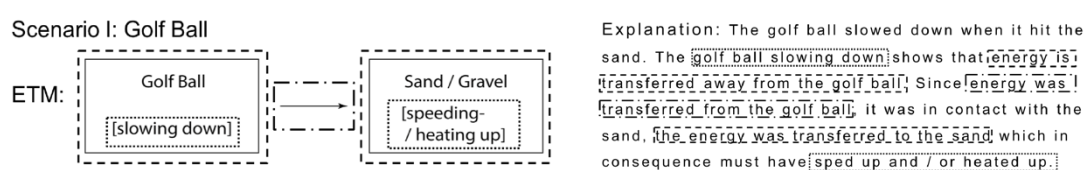


Figure 2. Correspondence between ETM (left) and non-ETM explanation (right).

For each element in the ETM, there is a corresponding element for the key ideas of systems, processes, and transfer in the non-ETM account.

In the ETM, the first key idea "systems", i.e., the interacting objects, are identified as the two boxes that are labeled "Golf Ball" and "Sand / Gravel" and are part of what is an ETM and thus related to energy. Similarly, in the non-ETM account, the systems are identified when the two objects are related to processes or energy transfers and thus the systems-transfer perspective.

ETM group students cannot just write "Ball" somewhere on the page to demonstrate that they identify interacting systems but have to write "Ball" in a box that is clearly part of an ETM. Students in the non-ETM group cannot just say "Ball" but have to use it in a discourse that features the elements of the systems-transfer perspective, e.g., "The sand and ball are the two interacting systems here."

To identify the second key idea "processes", that are going on in the respective systems, ETM group students have to write "slowing down" in a box labeled "Golf Ball" and non-ETM group students have to say something similar to "the golf ball slows down" in a way that relates the statement to the other elements (systems, energy transfer) of the systems-transfer perspective. For ETM students it is not enough to just write "slowing down" somewhere on the page but it has to be in the right spot within an ETM. Similarly, students that apply the systems-transfer perspective without an ETM cannot just describe the phenomenon and get credit but have to talk about the processes such as "slowing down" within a discourse that features the other elements of the systems-transfer perspective.

To identify the direction of the "energy transfer" as the third key idea, ETM group students have to draw an arrow pointing from a box labelled "Ball" to a box labelled "Sand" and non-ETM group students have to say something similar to "energy is transferred from the ball to the sand".

We used the rubrics in Table 1 and Table 2 to score students' ETMs and interviews.

The interviews were coded by a second coder and we found satisfactory inter-coder reliability between the coders (Cohen's Kappa  $\kappa = .87$ ). After an analysis of the conflicting codes, we were able to resolve those.

Table 3  
Scoring rubric used for ETM and non-ETM group for S1.

Aspect	NC (0)	PC (0.5)	FC (1)
System Sand	no/incorrect system identified	-	Sand/Gravel
System Ball	no/incorrect system identified	-	Golf Ball
Process Sand	no/incorrect process identified	increasing	speeding / heating up (sand / gravel)
Process Ball	no/incorrect process identified	decreasing	slowing down (golf ball)
Transfer Sand	no/incorrect transfer identified	-	Energy transfer to the sand / gravel system.
Transfer Ball	no/incorrect transfer identified	-	Energy transfer from the golf ball system.

Table 4  
Scoring rubric used for ETM and non-ETM group for S2.

Aspect	NC (0) Aspect	PC (0.5)	FC (1)
System Gravity	no/incorrect system identified	Gravity	Earth-ball gravitational field
System Ball	no/incorrect system identified	-	Basketball
Process Gravity	no/incorrect process identified	Gravity pulling / increasing	Earth-ball getting closer together
Process Ball	no/incorrect process identified	decreasing	speeding up
Transfer Gravity	no/incorrect transfer identified	Energy transfer from Gravity	Energy transfer from the Earth-ball gravitational field.
Transfer Ball	no/incorrect transfer identified	-	Energy transfer to the basketball

We applied the same scoring rubric to both groups because in both conditions students have equal opportunity to represent the systems, processes, and transfers they identified. In both scenarios a number of students used "increasing" and "decreasing" to refer to increasing or decreasing energy processes in the systems which we scored with a partial credit as it is ambiguous and imprecise. In S2, we found that a number of students mentioning

an energy transfer from "Gravity" instead of from the "Earth/ball gravitational field". As the idea of a gravitational field was new to students, we awarded this answer a partial credit.

**QUALITATIVE FEATURES IN HOW STUDENTS APPLY THE SYSTEMS-TRANSFER PERSPECTIVE.** We complimented the deductive approach using an inductive approach based on Mayring (2014) in which we looked for themes in students' reasoning not captured by the deductive scoring. In the inductive analysis we used phrases and sentences as coding unit and the complete discussion of a scenario as analytical unit. We examined all transcripts and selected anything that related to energy ideas and reasoning about those ideas. When statements appeared to allude to the same concepts, we used the same code, otherwise we coded those instances with a new code. While doing so, we conceived initial category definitions such as "students are using friction as an idea". After our first run through the material, we looked at our codes in light of the category definitions and refined the definitions by adding more detail. Codes that did not match the more precise category definitions anymore were dropped or if fitting, reassigned to a new category. At this point, we had identified four categories in the data: "using energy forms ideas", "using force ideas", "reasoning about hidden processes", and "reasoning about hidden systems". However, we dropped the "using energy forms ideas" category because we only found two students (one from each group) referring to forms ideas ("[...] first there is some kinetic energy [...] then it slowed down with friction on the ball.", "Wait, is it kinetic or potential energy that is stored"). While this might be surprising, it is in line with findings presented in (Fortus et al., 2019; Kubsch et al., 2019) and may be interpreted as evidence that students adapt the systems-transfer perspective very well and demonstrate little need for the idea of energy forms.

Based on our revised category system (Table 3) we ran through the material once more inspecting and revising our codes if necessary. After that, a second coder did another coding with the categories. Again, we found



satisfactory inter-coder reliability (Cohen's Kappa  $\kappa = .9$ ) and after an analysis of the conflicting codes we were able to resolve them.

***HOW IS THE CONSTRUCTION OF THE ETM LINKED TO STUDENTS REASONING?*** To investigate to what extent the ETM routinizes or constraints thinking, we used the smart pen data to analyze how students constructed the ETMs. We used our recordings to analyze how instances of the categories from the inductive analysis are conditional on how students constructed an ETM, i.e., we analyzed when we coded categories such as "reasoning about processes" relative to how students drew boxes, arrows, etc.

Table 3  
*Categories established for the inductive coding.*

Category	Definition	Anchor Example	Borderline Case
Reasoning about hidden systems	Questioning their own choice of systems, speculating about systems, and arguing for their choice of a hidden systems.	I wanna say it's gravity but it can't because it gotta be a physical thing.	I don't know etc. without further specification does not count. Further questioning where energy could be transferred also falls into this category.
Reasoning about hidden processes	Questioning their own choice of processes, speculating about a process, and arguing for their choice of a hidden process.	I don't really know what to put for the process, for the gravel, because it's not moving or anything.	I don't know etc. without further specification does not count.
Using force ideas	Students are using force ideas in their reasoning. They reason about interactions such as pushes or pulls between objects to explain the phenomenon.	And then once she let it go, gravity just pulled it down, just took it.	Friction and resistance are also considered force interactions.

## RESULTS

### ***HOW SUCCESSFULLY DO STUDENTS APPLY THE SYSTEMS-TRANSFER PERSPECTIVE?***

We assessed to what extent students applied the systems-transfer perspective on energy successfully to phenomena by scoring to what extent the

students were able to correctly identify the relevant systems, energy transfers and process in the two scenarios. By adding up these scores for each scenario we arrived at a score ranging from zero to six for each explanation. Table 4 shows the score distribution for both groups and scenarios. We divided the scores into high (no or only one element not correctly identified), medium (two or three elements not correctly identified), and low (more than three elements not correctly identified). While the number of students that score high is relatively similar in the ETM (11) and non-ETM group (9) for S1, the number of students that score low is considerably smaller in the in the ETM group (1) than in the non-ETM group (6).

In S2, student scores are more evenly distributed across the three levels (Table 4) but the number of low scoring students is still smaller in the ETM than in the non-ETM group.

Table 5  
*Number of students that scored low, medium, and high in both groups in S1 and S2.*

Scenario	Group	Number of Students		
		Low	Medium	High
S1 - Golf ball	ETM	1	3	11
	non-ETM	6	0	9
S2 - Basketball	ETM	3	7	5
	non-ETM	5	5	5

Looking at the sub-scores (Figure 3) explains why student scores in S2 are generally lower than in S1: Although students learned about magnetic fields, nobody used the idea of a field and thus students only received partial credits for processes and energy transfer sub-scores of the "Earth/ball gravitational field system" as the right panel of Figure 3 reveals.

Further, Figure 3 shows that across both scenarios ETM group students slightly but consistently scored higher than non-ETM group students on the sub-scores. A notable divergence is the "Process: Sand" sub-score. Here, both groups score relatively low but while ETM group students scored partial and full credits, non-ETM group students either scored full or no credit. As our scoring guide (Table 2) reveals, no credit means either no or wrong answer.

In light of the "Process: Sand" sub-score being a hidden, i.e., not clearly visible process, we took a closer look at that sub-score: we found that all students in the ETM group that scored no credit, put down a process that was incorrect, while all students from the non-ETM group that received no credit (12) did so because they did not address the process in the sand at all.

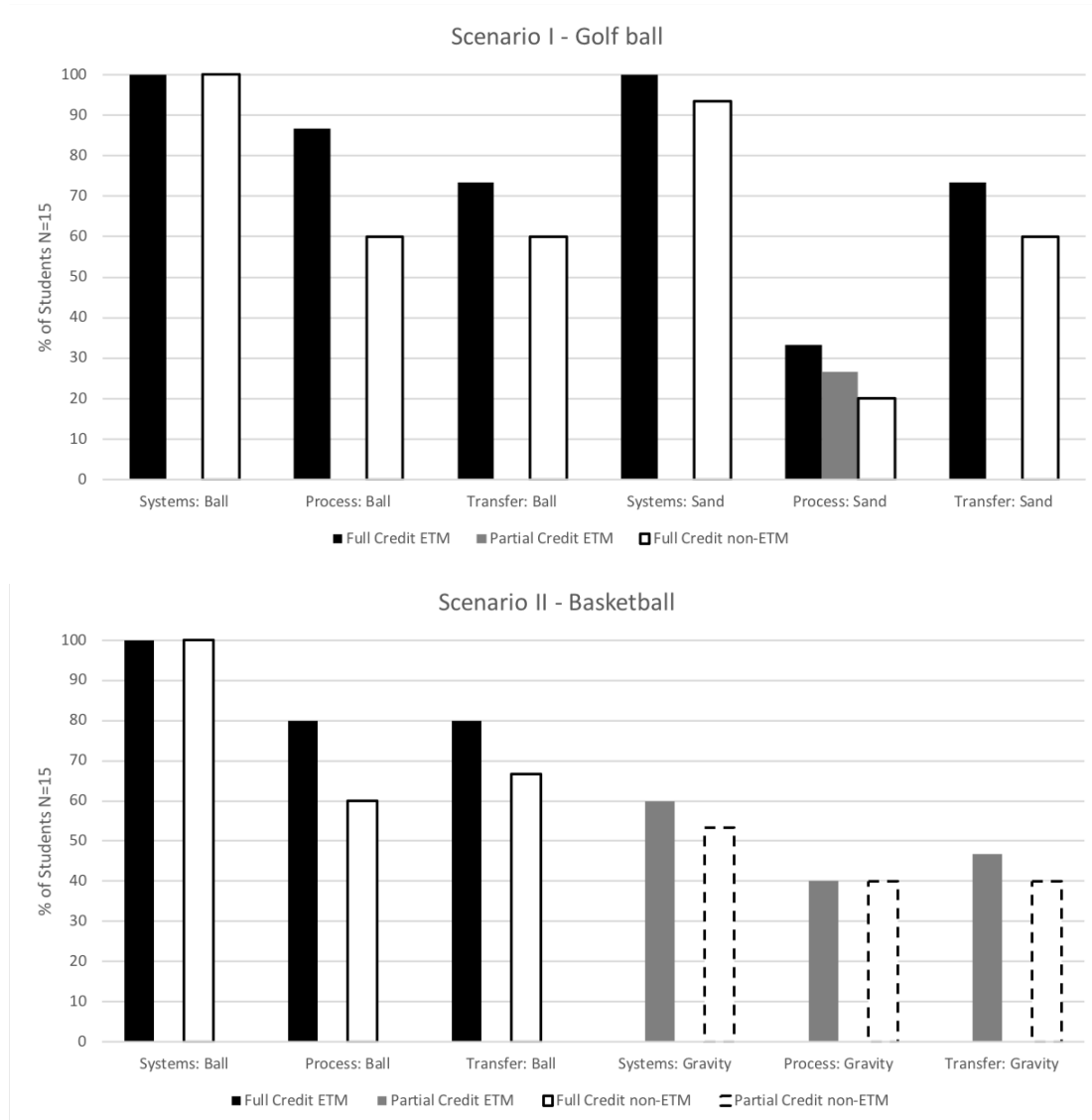


Figure 3. Distribution of sub-scores for ETM and non-ETM group in Scenarios 1 and 2.

In sum, we see students from the ETM group scoring slightly but consistently higher across both scenarios than students from the non-ETM group. In near transfer S1, most students scored high but the number of low scoring students is higher in the non-ETM group than in the ETM group. The sub-scores reveal that a majority of students from the non-ETM group failed to

address the hidden process in the sand system. In S2, scores were lower on average and more evenly distributed. The sub-scores reveal, that this is due to students not transferring the idea of fields successfully. This leads to a limited extent to which our scoring rubric can capture differences in student answers in S2.

***QUALITATIVE FEATURES IN HOW STUDENTS APPLY THE SYSTEMS-TRANSFER PERSPECTIVE***

To investigate to what extent students applied the systems-transfer perspective qualitatively different when constructing an ETM versus delivering a non-ETM account, we conducted a qualitative analysis during which we identified three categories (Table 3): using force ideas, reasoning about processes, and reasoning about systems. Further, we noticed that except for one student who verbally described an ETM no student in the non-ETM group referred to the ETM or chose to use the pen and paper at their disposal to construct an ETM.

***QUALITATIVE FEATURES OF STUDENT REASONING.*** We coded 15 instances in which students used force ideas to explain the phenomena, i.e., they referred to forces as pushes and pulls and tried to connect these ideas to the phenomena:

*"I think it's friction and collision and it slowed it down." (S1)*

*"And then, once she let go, gravity just pulled it down, just took it." (S2)*

Further, we coded eight instances in which students reasoned about the hidden processes in the sand system in S1 and the Earth/ball gravitational field system in S2. The following examples share that in each case the student is thinking about a hidden process:

*"I'm thinking about what the sand is doing, because the sand is not increasing, it is just stopping the golf ball." (S1)*

*"I just can't think of a process. It's just like pushing it down" (S2)*

Finally, we coded another 8 instances in which students reasoned about hidden systems, i.e. something like the environment in S1 or the Earth/ball gravitational field system in S2:

*"Because if the gold ball in the sand is decreasing the speed the that means the energy has to be going somewhere" (S1)*

*"I wanna say this is gravity but it can't be because it's gotta be a physical thing." (S2)*

In sum, the themes we identified were related to students using force ideas to make sense of phenomena and reasoning about the hidden systems and processes in both scenarios.

***DISTRIBUTION OF CATEGORIES ACROSS SCENARIOS AND GROUPS.*** Table 5 shows the distribution of the reasoning about hidden systems, and processes, and reasoning about forces codes across both scenarios and groups. Students in the ETM group reason more about the hidden systems and processes in the phenomena than non-ETM group students. In contrast, non-ETM students reason more about forces than ETM students (5 in ETM group 7 in non-ETM group).

Table 6.  
*Distribution of qualitative features in both groups in S1 and S2.*

Scenario	Group	Reasoning about hidden systems	Number of Students ...	
			Reasoning about hidden processes	Reasoning about forces
S1 - Golf ball	ETM	1	4	2
	non-ETM	1	1	3
S2 - Basketball	ETM	4	4	3
	non-ETM	2	0	4

In the background section we argued that a key feature of cognitive tools is to provide insights into phenomena that can help students to go beyond their current level and set the stage for future learning. From the systems-transfer perspective, reasoning about hidden systems and processes, can be considered such insightful uses. Across both scenarios Figure 4 shows the

distribution of reasoning about hidden systems and hidden processes for the non-ETM and ETM group. In total, 13 instances of insightful use (76%) are found in the ETM group and four in the non-ETM group.

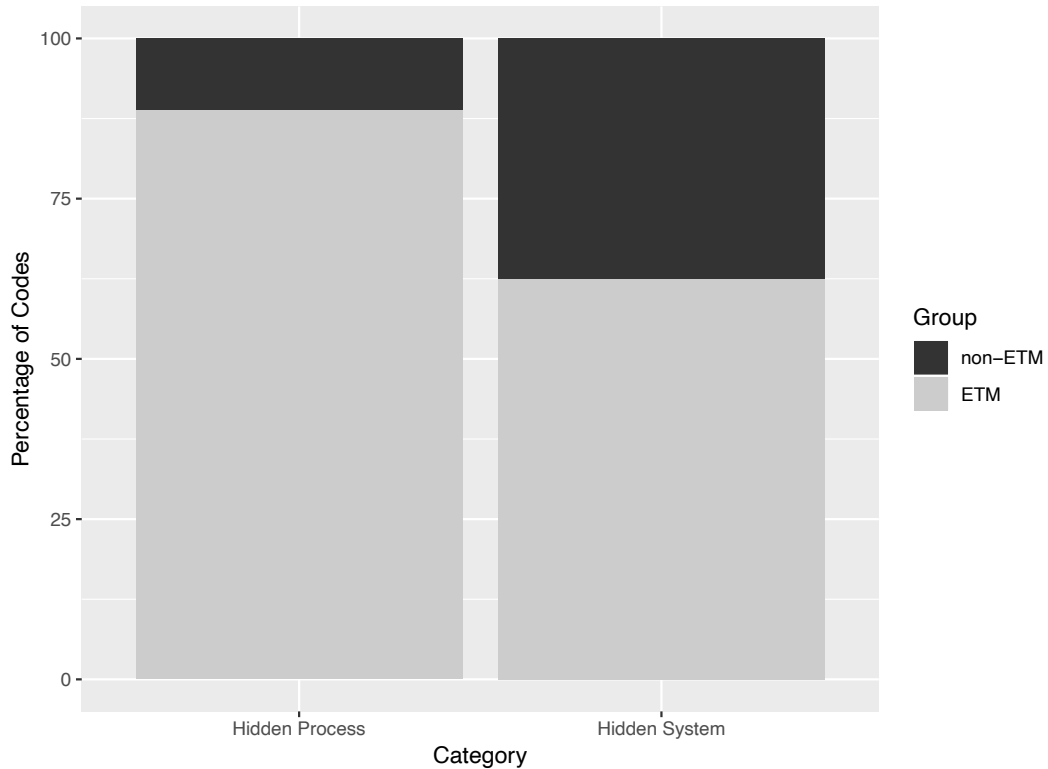


Figure 4. Percentage of reasoning about hidden systems and processes codes for non-ETM and ETM group.

In sum, students from the ETM group use the systems-transfer perspective more often to reason about hidden systems and processes such as the sand heating up in S1 or a hidden system such as air transferring energy to the basketball in S2. Further, although explicitly prompted to use energy-transfer ideas, students from both groups also relied on force ideas and more students from the non-ETM group than from the ETM group did so.

#### ***HOW IS THE CONSTRUCTION OF THE ETM LINKED TO STUDENTS REASONING?***

In S1 we found that the instances of "reasoning hidden processes" we identified in our inductive analysis all happened after students had completed their ETMs expect for the hidden process of the sand. In S2, we found that the instances of "reasoning hidden systems" and "reasoning about processes"

we identified in our inductive analysis are also closely linked to the construction of the ETM. After drawing box, arrow, box students filled in the "ball" system and the "increasing speed" process for the "ball" system. Then, they wondered what the other system could be (this is when we coded "reasoning about systems") and after they decided for a system wondered what the respective process could be (this is when we coded "reasoning about processes"). Figure 5 illustrates this pattern.

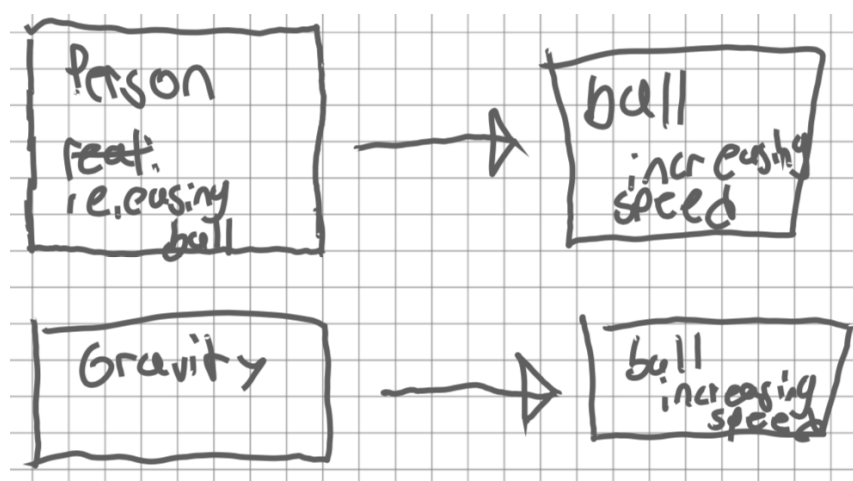


Figure 5. Illustrative example of an average scoring student.

The student first drew the upper ETM, starting with box, arrow, box and then filling in the "ball" system and the respective process "increasing speed". After putting down "Person" and "releasing ball" the student said: "Well it's not really getting the energy from the person 'cause they are just dropping it." Here, the student questions his choice of processes and in consequence his choice of system, i.e., is reasoning about the involved processes and systems. The student then draws a second ETM below the first one with a "Gravity" system and says: "Just can't think of a process. It's just like ... just like pushing it down". The student is considering what might be a process for a "Gravity" system but doesn't put any down. However, he is clearly reasoning about a process.

In sum, we found that the thirteen instances when students in the ETM group were reasoning about processes or systems were conditional on the construction of the ETM.

**DISCUSSION**

We investigated how constructing a specific representation (the ETM) supports students in applying the systems-transfer perspective on energy to interpret phenomena. Our results indicate that students who actively construct a representation as they apply the systems-transfer perspective are able to apply it more successfully than students who do not actively construct an ETM. Constructing an ETM seemed to help students to look for hidden processes and systems in the target phenomena and therefore more fully account for relevant energy transfers. A full accounting for energy transfers is necessary to begin developing a sense of energy conservation, and while conservation is not a goal of middle school energy instruction, fully accounting for relevant systems and processes in phenomena helps set the stage for future learning, both within a unit of instruction and over longer periods of time.

***A STOPPING GOLF BALL – HOW CONSTRUCTING A REPRESENTATION HELPS STUDENTS FULLY ACCOUNT FOR ENERGY TRANSFERS***

We considered the stopping ball phenomenon (S1) a near transfer task as it – unlike any phenomenon encountered by the students before – included a system without any visible process going on. Using a cognitive tool such as the ETM, makes it easier to infer the hidden processes and thus do better due to the structure that the construction of the representation imposes on the reasoning process (Chen et al., 2018; Kim & Reeves, 2007; Rumelhart & McClelland, 1986). This helps students to go beyond their current level and into the zone of proximal development (Vygotsky, 1978). The results from our deductive analysis support that students that construct an ETM are more successful in fully accounting for the systems, processes, and energy transfers than students from the non-ETM group: more students from the ETM group than from the non-ETM group score in the “high” category and fewer students from the ETM group score in the “low” category than in the non-ETM group (Table 4). Further, students from the ETM group are more successful in identifying the hidden process than students from the non-ETM group (Figure 3) that often did not address a process in the sand system at all.



But how did constructing an ETM “imposing structure on the reasoning process”? According to Iiyoshi et al. (2005) and in line with findings from Mayer (1997) and Paivio (1986) cognitive tools can e.g. help to identify relevant attributes while ignoring irrelevant ones and support learners in connecting new with existing knowledge. The results from our inductive analysis indicate that students from the ETM group are more likely than non-ETM group students to reason about the hidden processes going on in a system – a key attribute of the systems-transfer perspective. In addition, they use fewer force ideas – a concept that is rather irrelevant to explaining a phenomenon from a systems-transfer perspective. When we analyzed how students reasoned through the phenomenon, we found that the instances of reasoning about the hidden process identified in the ETM group were conditional on how students constructed the ETMs, that is they happened when students were constructing the process part of their ETM. Thus, our results suggest that the ETM functions as a cognitive tool as it helps students to focus on key elements of the systems-transfer perspective while ignoring concepts that are less important in applying the systems transfer perspective such as forces to which students are known to digress when asked to use energy ideas to interpret phenomena (Chabalengula et al., 2012; Gilbert, Watts, & Osborne, 1982).

Other authors, e.g., Scherr, Close, McKagan, et al. (2012) have put forward the theoretical argument that representations that emphasize transfer and thus depict energy as a quasi-material substance, support students in tracking energy successfully. Our results add to the literature as they add empirical weight to these theoretical considerations.

***A FALLING BALL – HOW CONSTRUCTING A REPRESENTATION SETS THE STAGE FOR FUTURE LEARNING***

S2 went beyond S1 in the sense that it not only included a hidden process and system but also had a forward-looking component with respect to the unit where gravitational energy was addressed right after our study, thus it required a more distal transfer than S1. The differences in scores between ETM and non-ETM students were less pronounced in S2 than in S1

(see Table 4 and Figure 3). This indicates that while the ETM has leverage into the zone of proximal development within the range of near transfer tasks, it is less effective to go further into the zone of proximal development as in S2 where student had to transfer the concept of fields from the domain of magnetic interactions to gravitational interactions.

Further, as in S1, the results from our inductive analysis suggest that in S2 students from the ETM group are more likely to look for hidden processes and systems than from the non-ETM group. As in S1, those instances are where found when students were constructing the respective parts of their ETMs. Students from the ETM group were looking for a system that could transfer energy to the ball and also speculating about potential processes in that system, but their answers remained normatively wrong. However, from the perspective of cognitive tools, this is an example of how the structure that cognitive tools impose on reasoning processes interacts with the learning environment as it can set the stage for future learning (Kim & Reeves, 2007; Vygotsky, 1978). For students who have identified that there has to be an energy transfer from some system to the falling ball, subsequent lessons that introduce the gravitational field as the system that transfers energy to the ball will address a need to know. Such a perceived need to know is important for integrating the idea of a gravitational field into students' knowledge structure (Linn, 2006). More generally, this shows that representations such as the ETM can be an important tool in establishing a need to know for students.

#### ***REASONING ABOUT THE HIDDEN SYSTEM OR PROCESS AND QUALITATIVE CONSERVATION***

When students were reasoning about the hidden systems or processes, they were recognizing that when the energy of a system changes, there has to be another change in energy in some other system. This reflects qualitative conservation, i.e., energy is always successfully tracked across systems, it is neither lost nor appears out of nowhere (Gray et al., 2019). Routinizing this qualitative notion of conservation that energy always has to be somewhere is a powerful foundation for building the quantitative notion of energy

conservation later. This notion is also featured in the quasi-material model of energy (Duit, 1987) where energy must come from one system and go to another and which has been shown to support students in progressing towards conservation (Kesidou & Duit, 1991). Recently however, Gray, Wittmann, Vokos, & Scherr, (2019) argued that a representation shows energy conservation only when it explicitly pictures the count of energy units throughout. This quantitative focus appears to dismiss the potential of qualitative conservation that we observed in this study when students were looking for another system because “the energy has to be going somewhere”. We advocate for recognizing that energy conservation can be represented quantitatively as well as qualitatively and that each way can support students in learning about conservation over time. In fact, such a qualitative perspective on energy conservation in middle school aligns with empirical and theoretical learning progressions (Herrmann-Abell & DeBoer, 2017).

### ***LIMITATIONS***

Due to the limited amount of variability that two scenarios impose, we cannot fully rule out that our results are influenced by the scenarios we chose. However, we carefully selected the scenarios for their deep structure, i.e., hidden systems and processes, and have no reason to believe that the surface structure either imposed additional challenges or provided additional support that could distort our results.

Students in the ETM group were not asked to think-aloud, thus we had to infer how constructing an ETM guided their reasoning from the patterns they followed and from spontaneous utterances. In consequence, our analysis might not have captured the full range of ways in which constructing an ETM can guide student thinking when applying the systems-transfer perspective to interpret phenomena and underestimate how often ETM group students reasoned about systems and processes. However, the aim of this study was to compare students that applied the systems-transfer perspective by constructing a representation with students that applied the systems-transfer perspective without constructing a representation. For non-ETM students, especially

without extensive training, the think aloud technique might have interacted with applying the systems-transfer perspective verbally and thus inhibited a comparison between the groups.

Lastly, we acknowledge that our sample size is too small to distinguish differences between ETM and non-ETM groups statistically and future studies would benefit from larger samples. However, our results align with the theory and support each other. For example, our scores show that ETM students scored higher on the hidden sand system sub-score in S1 than non-ETM students. Our qualitative analysis supports and explains this result as it revealed that almost all students that were actively reasoning about the process in the sand system were in the ETM group and did so conditional on the construction of the ETM, i.e., when they tried to fill in the process for the sand system.

#### **IMPLICATIONS**

Our study took place in the context of a particular systems-transfer unit and representations need to align with the learning environment to be effective, yet our results are also valuable beyond the systems-transfer perspective as the base structure of the ETM, i.e., boxes representing systems and arrows between boxes representing energy transfers, is common to representations of energy transfer such as energy tracking (Scherr et al., 2016) or PET diagrams (Goldberg, Robinson, & Otero, 2008). Still, future research could investigate the full range of widely used energy representations and also target the relative effectiveness of different energy representations with respect to the different energy aspects, e.g., energy bar or pie charts may both help students to identify the relevant forms of energy in a phenomenon, but pie charts may support the idea of energy conservation more effectively.

Our results indicate that constructing an ETM helps students to apply the systems-transfer perspective successfully, but students may not consciously perceive these benefits themselves, as no student from the non-ETM group used the pen and paper at their disposal to draw an ETM and only one student referred to the ETM at all. This might be an artifact of the interview

situation as we did not ask or encourage non-ETM group students to draw, but also points to an issue also identified by Karpicke & Blunt (2011): students may lack the metacognitive resources to judge when constructing a representation can be helpful. Thus, it appears worthwhile to spend time in the classroom on reflecting what (cognitive) tools are helpful in which situations: whereas a thermal imaging camera can help to reveal hidden energy transfers (Nordine & Wessnig, 2016), constructing a representation such as the ETM can lead to inquiry about hidden systems or processes.

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**PUBLICATION III:  
PROBING THE RELATION BETWEEN STUDENTS' INTEGRATED  
KNOWLEDGE AND KNOWLEDGE-IN-USE ABOUT ENERGY US-  
ING NETWORK ANALYSIS**

**ABSTRACT**

Modern science standards emphasize knowledge-in-use, i.e., connecting scientific practices with content. For knowledge to become usable in knowledge-in-use performances, students need well organized knowledge networks that allow them to activate and connect sets of relevant ideas across contexts, i.e. students need integrated knowledge. We conducted a longitudinal interview study with 30 students in a 7<sup>th</sup> grade energy unit and used network analysis to investigate students' integrated knowledge, i.e., their knowledge networks. Linking these results with results from knowledge-in-use assessments, we found a strong connection between integrated knowledge and knowledge-in-use about energy. Further, we found evidence that well-connected ideas around the idea of energy transfer were particularly helpful for using energy ideas in the knowledge-in-use assessments. We present network analysis as a valuable extension of existing approaches to investigating students' knowledge networks and the connection between them and knowledge-in-use.

## INTRODUCTION

Science standards such as the *US Next Generation Science Standards* (NGSS Lead States, 2013) or the German Bildungsstandards (Sekretariat der ständigen Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland, 2004) emphasize that a central goal of science education is that students are enabled to use their knowledge to make sense of the designed and natural world, i.e., students should be enabled to demonstrate knowledge-in-use by integrating disciplinary knowledge with scientific practices (Harris, Krajcik, Pellegrino, & McElhaney, 2016). For knowledge to become usable in such a way, students need to develop a well-connected knowledge network around central ideas of the domain as this facilitates retrieval and application (Bransford, 2000). The importance of knowledge networks organized around core ideas has also been recognized in modern educational standards, e.g., the NGSS emphasize "Disciplinary Core Ideas" and the German Science Standards introduced "Basic Concepts".

However, as Schwartz & Arena (2013) argue, science assessments often primarily focus on how much knowledge student have acquired instead of measuring to what extent students have an integrated knowledge. Students that have an integrated knowledge have well organized knowledge networks that allow them to activate and connect sets of relevant ideas across contexts. During the last decade, a number of authors have started to address this issue and developed different measures that describe to what extent students can connect ideas (Lee, Liu, & Linn, 2011; O. L. Liu, Lee, Hofstetter, & Linn, 2008; O. L. Liu, Ryoo, Linn, Sato, & Svihla, 2015; Nordine, Krajcik, & Fortus, 2011; Won, Krabbe, Ley, Treagust, & Fischer, 2017). These studies often use the knowledge integration perspective (Linn, 2006), which views learning as a process in which students develop increasingly better organized networks of ideas, i.e., while students learn, they (re)organize their knowledge networks around core ideas in a domain. These knowledge networks are considered to be the basis that allows students to demonstrate knowledge-in-use, i.e.,

connecting scientific practices, disciplinary core ideas, and cross-cutting concepts to interpret and explain real world phenomena (Harris et al., 2016).

Existing measures of students' knowledge networks either provide quantitative information about the extent to which students have organized knowledge networks (e.g., Lee & Liu, 2010) or qualitative information about how students organize their knowledge networks (Won et al., 2017). Neither approach links their results to knowledge-in-use in the sense of connecting practices, content, and cross-cutting concepts. In consequence, the relationship between students' knowledge-in-use and integrated knowledge in a domain is only little researched. In this paper, we present a network analytical approach that provides qualitative and quantitative information about students' integrated knowledge, i.e., how students activate and connect ideas, and explore connections between quantitative network measures and knowledge-in-use.

This study is part of a broader project on the teaching and learning of energy in middle school. As students have been shown to hold a wide range of ideas about energy, the energy concept provides an excellent venue to explore how network analysis can help to investigate students' knowledge networks and their relationship to students' ability to demonstrate knowledge-in-use. As the knowledge-in-use assessments used in this study have been described in depth elsewhere (Fortus et al., 2019), we only revisit them relatively quickly in this paper.

## **BACKGROUND**

### ***INTEGRATED KNOWLEDGE AND KNOWLEDGE-IN-USE***

Knowledge, or more specifically the organization of knowledge, is often characterized as a network-like structure (e.g., Anderson, 1983; National Academies of Sciences, Engineering, and Medicine, 2018). This characterization has been recognized and successfully applied in neuro- and cognitive science (Griffiths, Kemp, & Tenenbaum, 2008; McClelland & Axel Cleeremans,

2009; Park & Friston, 2013; Thagard, 2000). Synthesizing findings from psychology, the learning sciences, and educational research, learning can be viewed as a process in which students' knowledge networks undergo a process of restructuring, i.e., students add new ideas to their knowledge networks, sort out ideas, and establish, change, refine, and strengthen the connections between ideas (diSessa & Sherin, 1998; Linn, 2006). If certain ideas are commonly activated together and across a range of instances, they form patterns of activation which represent conceptual understanding (Derry, 1996). Within these patterns of activation, some ideas have larger span (diSessa, 2013), i.e., some ideas are more strongly connected than others and serve as hubs that connect multiple ideas. Those hubs represent core ideas in a domain. Further, patterns of activation become more likely to be activated in certain contexts if they prove to be of explanatory value, i.e., they can be used productively to interpret and explain phenomena (Smith, diSessa, & Roschelle, 1994). In sum, students that have an integrated knowledge have well organized knowledge networks around core ideas which allow them to activate and connect relevant ideas across context.

This perspective on learning resonates well with major findings from the cognitive sciences and science education. The focus on the restructuring of idea networks acknowledges that students come to the classroom with strong assumptions about how the world works (Bransford, 2000) and that this prior knowledge plays an important role in any learning process. Science education research has identified many of these conceptions or frameworks (e.g. Watts, 1983) and developed strategies to engage them by pointing to the superior explanatory value of their scientific counterparts (e.g. diSessa, 1988). Research on differences among novices and experts has revealed that novices and experts have differently organized knowledge networks (e.g. Chi, Feltovich, & Glaser, 1981). Chi et al. (1981) found that in the context of physics, experts used core ideas such as the principle of energy conservation to make sense of phenomena while novices relied on surface features of the phenomena. In essence, the knowledge of experts is well-organized around core ideas in the domain like energy conservation while the knowledge of novices

typically exists as a set of loosely connected or disconnected ideas, resulting in novices and experts often perceiving the same phenomenon differently – experts are more likely to notice deep structure while novices are commonly drawn to the surface features that experts ignore (Hmelo-Silver & Pfeffer, 2004).

Recent science standards such as the NGSS or the German science standards emphasize that a central goal of science education is to enable students to apply their knowledge in the context of scientific practices in a wide range of contexts (Harris et al., 2016), i.e., to demonstrate knowledge-in-use. To be able to connect disciplinary ideas, scientific practices and cross-cutting ideas to make sense of a range of phenomena, students need knowledge networks that are organized around core ideas of the domain, that is, integrated knowledge (Bransford, 2000; diSessa, 1988; Linn, 2006; Schneider & Stern, 2009). From an instructional perspective, the question arises which of the possible organizations of knowledge networks help to promote knowledge-in-use. More specifically, we might ask what is the relative importance of ideas in a given domain or what ideas are better suited as core ideas for an integrated knowledge? As studies usually focus either on knowledge-in-use (Harris, Krajcik, Pellegrino, & McElhaney, 2016) or integrated knowledge (e.g., Lee & Liu, 2010) there has been little research into the relationship between the two. Further, existing measures of how students connect ideas largely focus either on qualitative features of students' knowledge networks but do not connect those results to students' performance on related knowledge-in-use assessments (Won et al., 2017) or distinguish broader levels of connectedness in students' knowledge networks that relate to students' performance on related assessments (not knowledge-in-use assessments) but provide little information about how students actually connect ideas (Lee & Liu, 2010).

**EXISTING MEASURES OF INTEGRATED KNOWLEDGE**

In order to measure integrated knowledge i.e., how students organize their knowledge networks and activate and connect ideas to make sense of phenomena, researchers have taken a number of approaches, making different assumptions and using different testing formats: Kauertz & Fischer (2006) used multiple choice (MC) tasks, Lee & Liu (2010) constructed response (CR) tasks, Nordine et al. (2011) used interviews, and Won et al. (2017) used concept mapping.

**MULTIPLE CHOICE TASKS.** Kauertz & Fischer (2006) used a measure of six different levels of complexity that distinguished the number of ideas and the number of connections between those ideas. Low complexity was characterized by disconnected individual ideas, while high complexity was related to systemic connections between ideas organized around core ideas in a domain. Thus, the complexity measure targets different qualitative stages in students' knowledge networks. Using the complexity framework, Kauertz and Fischer designed MC tasks that match the different levels of complexity. More precisely, Kauertz & Fischer defined which ideas students had to link to answer a question correctly at the different levels of complexity, e.g., on a lower complexity level a student might have to link a form of energy with speed, on a higher complexity level a student might have to link two forms of energy with the idea of energy transformation. While the choices for linking ideas such as "energy transformation" are reasonable, they might not reflect the ideas that students actually used when answering the question as MC tasks allow for guessing or other test-wiseness related strategies (Pellegrino, Chudowsky, & Glaser, 2004). However, using IRT modeling, they found a strong and highly significant correlation between the complexity levels that they had assigned to the tasks and task difficulty. By mapping individual ability and task difficulty using IRT, Kauertz and Fischer concluded that students that score higher are able to elaborate more complex scientifically valid links among ideas relevant to the tasks, i.e., that higher scoring students have better organized knowledge networks.

**CONSTRUCTED RESPONSE TASKS.** Liu, Lee, Hofstetter & Linn (2008) established one approach that was tested and refined over multiple studies (e.g., Lee & Liu, 2010). In this approach a combination of multiple choice (MC) and constructed response (CR) items are used (see Figure 1 as an example).

The source of energy for the earth's water cycle is the

- (a) Wind
- (b) Sun's radiation
- (c) Earth's radiation
- (d) Sun's gravity

Explain your choice.

Main Ideas:

- Sun idea: Sun warms (heats) up earth.
- Evaporation idea: Water is evaporated (water changes from liquid to gas or water vapors).
- Condensation idea: Water changes from gas to liquid to form clouds.
- Precipitation idea: Different types of precipitation fall from sky.
- Energy idea: Energy is required in evaporation.
- Water cycle idea: Water cycle consists of evaporation, condensation, and precipitation.

Links:

- Sun–energy link: Sun's radiation energy is used for evaporation of water.
- Evaporation Link: Water molecules are broken apart from the surface of the liquid water.

Knowledge Integration Level	Criteria	Examples
<b>Irrelevant:</b> Off-task	Wrote some text unrelated to the item.	<ul style="list-style-type: none"> <li>• Because I think so.</li> </ul>
<b>No-link:</b> Nonnormative ideas	Elicited nonnormative ideas or restated the multiple-choice answer chosen.	<ul style="list-style-type: none"> <li>• Sun's radiation gives light to the water cycle.</li> <li>• Wind moves the water through the air.</li> </ul>
<b>Partial-link:</b> Normative ideas	Elicited any one idea listed above.	<ul style="list-style-type: none"> <li>• Sun warms up water.</li> <li>• Sun evaporates water.</li> </ul>
<b>Full-link:</b> Single link between two normative ideas	Used either sun–energy link or evaporation link.	<ul style="list-style-type: none"> <li>• The water molecules are broken off from the surface of the water.</li> <li>• Sun heats up the water to evaporate.</li> </ul>
<b>Complex-link:</b> Two or more links among three or more normative ideas	Used either sun–energy or evaporation link and added an additional idea or link listed above.	<ul style="list-style-type: none"> <li>• The sun's radiation makes the water evaporate in to the air which goes through evaporation, condensation, then precipitation.</li> </ul>

Figure 3. Wcycle item (IEA, 1999) and knowledge integration scoring rubric.

Figure 1. Example for items and knowledge integration rubric used by Lee & Liu, (2010).

Beginning with the MC part, a phenomenon is presented, and students have to choose the correct answer. In the associated CR part, students are asked to explain or justify their answer from the MC part. The extent to which students are able to connect ideas identifiable in the explanations is then coded on a scale from not linking relevant ideas ("no link") through an

intermediate level of linking ("partial link") to the level of elaborating a scientifically valid link between two ideas relevant to a given context ("full link"). A further "complex link" level is identified when students use more than one link between at least three ideas, but only very few students reach that level (Lee et al., 2011). The authors use IRT models to link the scales of the MC questions to those of the CR question. Higher levels of performance on the MC questions map onto higher levels of performance on the CR questions, thus linking higher test scores to higher levels of connecting ideas. Thus, the study supports the relationship between better organized knowledge networks and performance on related assessments found by Kauertz & Fischer (2006). Further, Lee & Liu (2010) measure how students connect ideas less distal than Kauertz & Fischer (2006) as they observe the extent to which students link ideas in their answers directly. However, as Lee & Liu (2010) note, the extent to which students connect ideas may be underestimated due to students' known lack of commitment to formulating scientific explanations. Students who are not motivated to explain their choice or not motivated to do so in a thorough way will link few if any ideas in their explanations.

**INTERVIEWS.** Nordine et al. (2011) measured which ideas students connect in the domain of energy using an interview about instances approach (Osborne & Gilbert, 1980). In this approach, the interviewed student is presented pictures that illustrate various everyday situations and asked whether the pictures illustrate their idea of energy. If the student answers "yes", the interviewer asks for the students' reasoning. If students use ambiguous wording the interviewer can, using the language of the student, probe into the students' reasoning to clarify what is meant. To measure how students connect ideas from these interviews, the researchers used a qualitative analysis to determine whether the students used "transformation" to link at least two forms of energy (kinetic energy etc.). This level of connecting ideas appeared to be equivalent with a middle ground between the "full link" and "partial link" level identified by (Lee et al., 2011). Thereby, how students connect ideas was dichotomously assigned to represent either at least a "partial link" level or to be below the "partial link" level. The level of connecting ideas was



significantly correlated with students' scores on an energy concept questionnaire adapted from Swackhamer & Hestenes (2005). This supports that better organized knowledge networks are in fact related to higher performance in interpreting and explaining phenomena using core ideas in a domain. While measuring how students connect ideas on a coarser grain size than Lee & Liu (2010), the interview approach can help to counter the motivational issues in the Lee & Liu (2010) approach and is potentially more sensitive to developmental stages in students' knowledge networks where students may not yet be able to articulate links between ideas in a written form.

**CONCEPT MAPPING.** Won et al. (2017) asked students to draw concept maps (Novak, 1990) on the topic of energy and used the multiple choice energy concept assessment from (Neumann, Viering, Boone, & Fischer, 2013). Concept maps provide vivid representations of how students connect ideas and allow to distinguish qualitative differences in how students connect ideas. Different features related to students' knowledge networks, e.g., the number of ideas in a map or the number of connections between ideas, can be used to score the maps. However, the scoring of the maps employed by Won et al. (2017) is only weakly related to how students perform on the energy concept assessment. Won et al. (2017) identify various issues such as students' inexperience with the concept mapping task that may explain the unexpectedly weak relationship between students' concept maps and their performance on the energy concept assessment. In addition, we consider concept maps problematic for how students connect ideas to make sense of phenomena, as they are typically constructed by the students themselves. There is a threat to validity in this approach: a student may certainly be able to draw a concept map that connects two relevant ideas, e.g. energy transformation and different forms of energy, but not be able to apply those ideas when asked to make sense of a phenomenon and vice versa. Thus, concept maps may be suited to assess the structure of students' declarative knowledge (Ruiz-Primo, 2004) but appear less suited to assess students' ability to link ideas to make sense of phenomena, i.e., students' integrated knowledge.

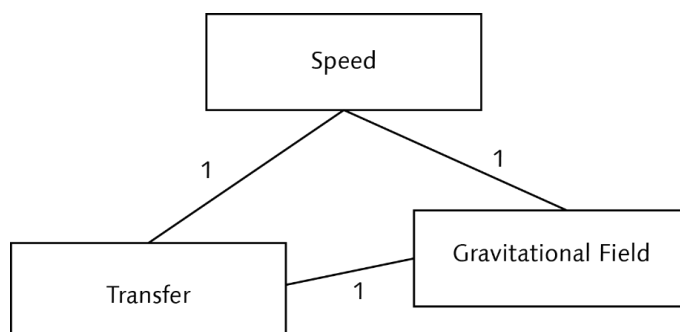
In summary, the MC, the CR, and the interview approach to measuring students' integrated knowledge found a strong relation between different levels of connectedness in students' knowledge networks and performance on related assessments (although not knowledge-in-use assessments). The MC approach hinges on the assumption that one can reliably infer the ideas that a student has connected from the answer he gives on a MC test. The CR approach assigns levels of knowledge integration based on the extent to which a student uses specific a priori defined linking ideas. The same is true for the interview approach which is potentially more sensitive to less developed stages of knowledge integration than the CR based approach. Finally, the concept mapping approach does not find a strong relation between students' knowledge networks as assessed by concept mapping and students' performance on related MC assessments but provides insight into qualitative differences in how students connect ideas.

#### ***MEASURING INTEGRATED KNOWLEDGE USING NETWORK ANALYSIS***

We propose to synthesize the existing approaches to measuring how students connect ideas through the application of network analytical tools. First, consider again the definition of integrated knowledge: it describes students' ability to coordinate a set of core ideas consistently across phenomena to make sense of them. Thus, we propose, similar to the CR or interview approach, to measure which ideas students use when interpreting and explaining phenomena. However, instead of assessing whether students use a priori defined linking ideas and assigning respective knowledge integration scores, we draw on the central assumption that all ideas a student uses in response to a phenomenon, are connected. We consider this assumption, which is used with great success in automated semantic analysis (Landauer, 2014), automated coding of student responses (e.g. Zehner, Sälzer, & Goldhammer, 2016), or classification of texts (Blei & Lafferty, 2007), warranted because we aggregate across phenomena and do not interpret co-occurrences of ideas in a single phenomenon. When we aggregate across phenomena, sets of ideas that co-occur across many phenomena appear to be stronger linked than

those sets of ideas that are only used in a single phenomenon or across few phenomena. Stronger linked ideas should reflect core ideas in a domain as - following the definition above - the central feature of core ideas is that they are used consistently across phenomena. Following this approach leads to relational data that can be visualized as a network. Similar to a concept map, the network should reveal major characteristics of how students link ideas, yet these maps are generated by analyzing students' use of a concept when making sense of phenomena rather than mapping the concept itself. In addition, network analytical methods allow for the quantification of aspects of the networks which can then be related to students' performance on knowledge-in-use assessments. In the following, we will describe how knowledge networks can be constructed and quantitatively analyzed.

**FROM IDEAS TO NETWORKS.** To derive networks from student explanations of a range of phenomena, we draw on the central assumption that ideas that co-occur within a student's response to a single phenomenon are connected and that repeated co-occurrence (across multiple phenomena) is an indicator for the strength of the connection. In the following, we provide an example for an individual student that has explained two phenomena A and B. Assume that the student used the ideas speed, transfer of energy and gravitational field in his explanation of phenomenon A. This leads to a network for phenomenon A in which all three ideas - speed, transfer of energy and gravitational field - are connected with each other (Figure 2).



*Figure 2.* Example of network for one student and one phenomenon. Lines between boxes represent co-occurrence and the number next to the lines indicated frequency of co-occurrence.

Now assume that the same student uses the ideas speed, heat, and transfer of energy in the explanation of phenomenon B. Now, combining the networks for phenomenon A and phenomenon B results in a network (Figure 3) in which we add the idea heat to the existing network for phenomenon A and connect heat to speed and transfer of energy.

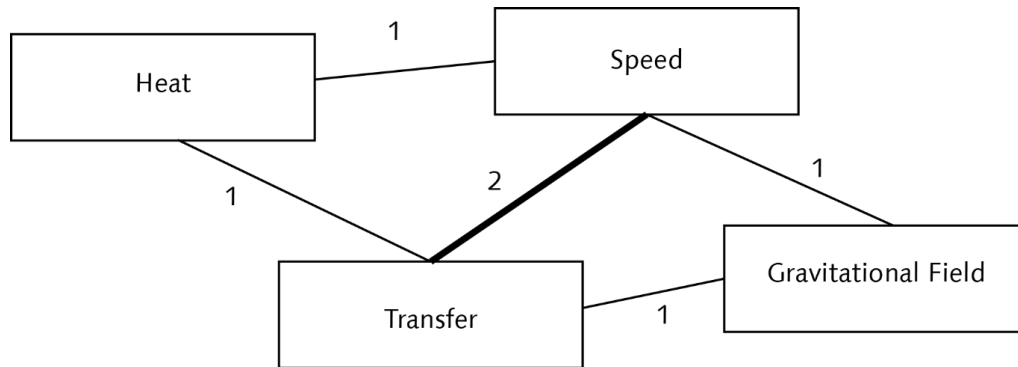


Figure 3. Example of network for one student for two combined phenomena. Lines between boxes represent co-occurrence and the number next to the lines indicated frequency of co-occurrence.

Further, since speed and transfer of energy co-occur in phenomenon A and phenomenon B, we increase the strength of the connection between speed and transfer of energy which is represented by the increase in width of the line connecting the ideas in Figure 3. In the same manner, we can combine networks across more of phenomena. Further, aggregating across individual-level networks gives collective networks, e.g., for students in a classroom. Such aggregated networks can be useful for understanding the prevalence of ideas and connections that exist in student populations (Loh & Subramaniam, 2018).

**QUANTIFYING NETWORKS.** Visual inspection of the network tells us which ideas co-occur and how often they do so. Network analysis provides the tools to construct numerical measures that help to quantify knowledge networks with respect to integrated knowledge.

*The role of single ideas.* Not all ideas are equally important and powerful to make sense of phenomena. Central ideas of a domain that serve as hubs that connect multiple ideas are more powerful as they are applicable across a

range of phenomena and contexts (National Research Council, 2012). For example, the idea that kinetic energy is related to the square or speed is correct, but not as central or broadly applicable as the idea that energy is conserved. Core ideas serve as linking ideas in knowledge integration measures (Lee & Liu, 2010) and have a larger span (diSessa, 1988; diSessa & Sherin, 1998). With respect to our networks this translates to the strength of the connections of a single idea to the remainder of the network. Network analysis offers a range of so-called centrality measures that capture this idea (Freeman, 1978). The simplest of these is degree and it captures how connected an idea is to the remainder of the network. Degree quantifies the number of other ideas a single idea is connected to, taking the strength of the connections into account, e.g., energy transfer in Figure 3 has a degree of four (one connection to heat, one connection to gravitational field, and one connection of strength two to speed) and heat has a degree of two. Thus, the higher degree of energy transfer with respect to heat reflects that energy transfer was used across more phenomena and in coordination with a broader range of ideas than heat. Note that the numerical values of network measures are often only meaningful relative to other networks that were created using the same process and often have little meaning on their own.

*A network measure of integrated knowledge.* Higher levels of integrated knowledge are typically associated with increasingly interconnected coordination of ideas, assuming that the ideas that are normative (Anderson & Schunn, 2000; Bransford, 2000; diSessa, 1988; Koponen & Huttunen, 2013; Linn, 2006; Rumelhart & McClelland, 1986). To quantify how interconnected a network as a whole is, we draw on what Rafols & Meyer (2010) call network coherence. To calculate network coherence, we calculate the closeness (Freeman, 1978) for each idea to each other idea and average across all ideas. Closeness  $C$  is defined as the inverse of the sum of the distance  $d$  between a single idea  $x$  and all other ideas  $y$  in the idea network:

$$C(x) = \frac{1}{\sum_y d(y, x)}$$

In the formula,  $d(y, x)$  is the shortest path between any two ideas. In our idea networks, we would consider energy transfer and speed strongly connected with a connection strength of 4 when a student uses those two ideas in four out of five phenomena. To interpret the strength of connection between ideas as a distance, we simply take the inverse of the strength of connection between two ideas to ensure that strong connections between ideas reflect short distances and vice versa. Let us provide an example: consider the network in Figure 2. To ensure that strong connections reflect short distances we simply take the inverse. Thus, the shortest path between the stronger connected ideas energy transfer and speed becomes 0.5, whereas the shortest path between the looser connected ideas energy transfer and heat becomes 1. Following the formula, the closeness of energy transfer is 0.4 as adding the shortest paths between energy transfer and heat, energy transfer and speed, and energy transfer and gravitational field gives 2.5 ( $1+0.5+1$ ) and the inverse of 2.5 is 0.4. Following the same procedure for gravitational field gives 0.25 (the inverse of  $1+1+2$ ) which reflects that gravitational field is less strongly connected with the remaining network than energy transfer. Averaging across the closeness of each idea in the network gives a network coherence of 0.325. Compare the network in Figure 3 with the network in Figure 4.

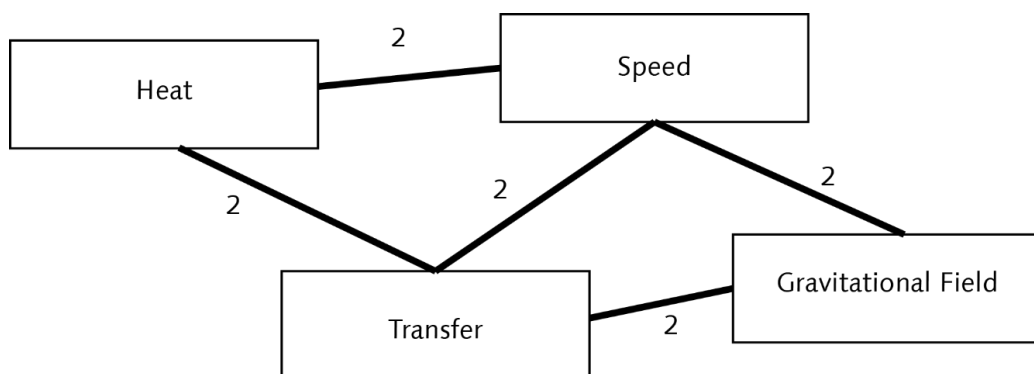


Figure 4. Example of network for one student for two combined phenomena. Lines between boxes represent co-occurrence and the number next to the lines indicated frequency of co-occurrence.

The network in Figure 4 suggests that the student used all four ideas in both phenomena, demonstrating a more integrated knowledge as she

coordinated a larger number of ideas consistently across phenomena than the student from the network in Figure 3. The measure of network coherence reflects this as it takes the larger value of 0.58. Similar to degree, network coherence has no natural scale, i.e., the numerical value can be used to compare different networks that were created using the same process but has no meaning of its own. To account for different numbers of ideas in networks, network coherence can be normalized by multiplying it with the number of ideas in a network (Freeman, 1978). In sum, network coherence is high in dense networks with strong connections and low in sparse networks with weak connections and should thusly provide a holistic measure of integrated knowledge.

### ***RESEARCH QUESTIONS***

To investigate to what extent how students connect ideas as measured by coherence is related to students' knowledge-in-use, and to what extent the proposed network analytical approach illuminates how qualitative differences in students' knowledge networks are related to students knowledge-in-use, we asked the following research questions:

RQ1: Over the course of instruction, how is the change in students' integrated knowledge as measured by a network analytical approach related to the change in students' knowledge-in-use?

RQ2: What qualitative information about students' knowledge networks does the network analytical approach provide and how is this related to students' knowledge-in-use?

### **METHODS**

To address the research questions, we conducted semi-structured interviews before and after a middle school unit about energy. In the interviews, students were presented brief videos of five different phenomena and asked to explain them. We then used network analytical methods to characterize and represent how students organized their ideas within idea networks and

to assess the extent to which students developed an integrated knowledge over the course of the instructional unit.

We assessed students' knowledge-in-use about energy using distal, NGSS aligned knowledge-in-use assessment before and after the energy unit and linked students' performance on those tasks to how students' idea networks changed over the course of instruction.

In the following sections, we describe the energy unit, describe our data sources, and then focus on how we analyzed the interviews to create representations of students' idea networks.

### **SAMPLE AND SETTING**

Our study was conducted as part of a larger project investigating the teaching and learning of energy in middle school. The learning environment consisted of an approximately 10-week long energy unit (Nordine et al., 2019) that emphasized energy transfers in interpreting and explaining phenomena as emphasized in the NGSS (NGSS Lead States, 2013). The energy unit was enacted by three teachers in the 7<sup>th</sup> grade of two rural middle schools located in the Midwestern United States. A sample of  $N = 30$  students, representing approximately 10% of the total sample of  $N = 294$  students, was interviewed. The teachers selected the students based on a request from the researchers to identify a sample of students who they felt would be comfortable being interviewed and who represented a range of student abilities in their classes. To test the representativeness of our interview-sample for the whole sample, we compared our interview sample to the sample as a whole based on students' average grade and gain on the unit's pre / post-test (Table 1).

Table 1  
*Mean and standard deviation for average grade across science, math, and English (11 point scale), and learning gain (z-Score) between whole sample and interview group.*

	Group	M	SD
Average grade	Interview group	8.10	3.74
	Whole Sample	6.67	3.75
Learning gain	Interview group	0.47	0.70
	Whole Sample	0.44	0.54



Although the differences between interview sample and the sample as a whole on both measures (gain:  $t(234) = 0.32$ ,  $p = .75$ ,  $d = 0.07$ ; average grade:  $t(234) = 1.52$ ,  $p = .13$ ,  $d = 0.38$ ) are statistically not significant, they indicate that our interview sample consisted of slightly higher achieving students.

### ***ENERGY IDEAS IN THE UNIT***

Prior to the unit, we expected students' ideas about energy to be relatively disconnected and mostly about different forms of energy and some ideas about the transformation of energy which they may have picked up in earlier learning opportunities (Chen et al., 2014). From the literature on student conceptions of energy (for an overview see Duit, 2014) and students usage of energy ideas to solve problems (Chabalengula, Sanders, & Mumba, 2012; Driver & Warrington, 1985) we expected that prior to the unit, students would rarely use energy ideas to explain and interpret phenomena and instead use ideas such as forces and everyday interactions between objects.

This study is situated in an energy unit (Nordine et al., 2019) that emphasizes energy transfers between systems as envisioned in the Framework for K-12 Science Education. The so-called "systems-transfer approach" is a transfer-only approach and does not distinguish between different forms of energy but instead treats energy as a unitary entity. During phenomena, interacting systems transfer energy between them and in parallel, each system undergoes a process that changes the amount of energy the system has. Energy conservation is implied because when energy is transferred from a system, it is always transferred to another system. Therefore, we would expect that, at the end of the unit students should have developed idea networks that are organized around the central idea of energy transfer and are able make sense of phenomena using those ideas, i.e., demonstrate knowledge-in-use about energy. Other energy ideas such as forms of energy or energy transformations should play a less significant role.

**DATA SOURCES**

**INTERVIEWS - PROTOCOL AND PHENOMENA.** To gain insight in how students connect ideas to make sense of phenomena, students were interviewed individually according to a semi-structured interview protocol. In this protocol, students were shown short (5-10 second) videos of five different phenomena and prompted to explain each one. After introductions and obtaining student consent, we showed students the video of the first phenomenon and asked: "How would you explain this phenomenon?". After students' initial answer, non-instructional prompts were used to clarify ambiguous statements and elicit which ideas students used, e.g. if a student referred to energy transfer to/from an object, the interviewer might ask "What do you mean by energy transfer?" After prompting, students were shown the video of the next phenomenon.

The pre and post interviews were identical and addressed five phenomena: a cup above a burning candle that starts spinning, a bouncing ball that eventually stops bouncing, melting ice<sup>1</sup>, a person pushing a barrel up a ramp, and an electric heater heating up (all phenomena are available as online supplemental). The phenomena were selected to cover a broad range of phenomena and topics (thermodynamic, mechanics, electricity, biological systems, etc.) and to be rich in the sense that one could interpret and explain them on different levels of detail (e.g., using a macroscopic or particle perspective to explain melting ice).

**KNOWLEDGE-IN-USE ENERGY ASSESSMENTS.** We used NGSS-aligned knowledge-in-use assessments to investigate how students' performance at interpreting and explaining phenomena using energy ideas changes over the course of the unit. The assessments were distal in the sense that they are not aligned to what was taught in the unit but the NGSS energy performance expectations for middle school. The assessments emphasized knowledge-in-use, i.e., blending a disciplinary knowledge (in this case about energy) with science practices such as constructing an explanation and cross-cutting ideas such as systems (Harris et al., 2016). The tests included twelve open-ended

tasks. We used evidence-centered design as laid out in the NRC report on Developing assessments for the Next Generation Science Standards (Pellegrino et al., 2014) and more specifically following the procedure by (Harris et al., 2016) to ensure that the tasks blended scientific practices, disciplinary core ideas, and cross-cutting practices, i.e., the task were designed to capture knowledge-in-use. Eight of those tasks were aligned to the NGSS energy middle school performance expectations and four to the K-5 energy performance expectations. The tasks were scored by experienced teachers (average percentage agreement across all tasks: 83%). We used a polytomous IRT model (Bond & Fox, 2015) to calculate students' knowledge-in-use ability. The infit and outfit of the items was between 0.90 and 1.20 and reliability was found to be 0.76.

### **ANALYSIS**

**CODING – FROM INTERVIEWS TO IDEAS.** As a first step, we transcribed all interviews. Then we used qualitative content analysis (Mayring, 2014) to determine which ideas students' used in their explanations. We followed a deductive approach in which phrases served as a coding unit and the complete explanatory account of one phenomenon as context unit, i.e., the number of times a student mentioned an idea such as speed in his or her explanation of one phenomenon was not accounted for. The deductive categories consist of numerous energy ideas and other scientific concepts (e.g., gravity, forces, or the particle model of matter) that students could use to construct scientifically valid explanations of the phenomena. We referred to literature on energy learning progressions (e.g., Neumann, Viering, Boone, & Fischer, 2013) to identify relevant energy ideas (e.g., forms, transfer, transformation). For all other concepts we considered grade band appropriate conceptions, e.g., for the concept of "force" we considered the respective literature on student conceptions (Gilbert, Watts, & Osborne, 1982) and labeled the resulting code "pushes / pulls". An example of our category system can be found in Table 2.

In some cases, interviewers asked the student to describe the phenomenon prior to explaining it. Ideas mentioned in a merely descriptive part were not coded. Further, in some cases the interviewers used instructional prompts (e.g. directly prompting for energy). In these cases, anything after such prompts was ignored. If instructional prompts occurred in more than one scenario, we excluded the interview because ideas potentially introduced by the interviewer would distort our results. In consequence, data from 13 students were excluded from the analysis because of instructive prompts. The remaining sample of  $N = 17$  students represents 7% of the total number of 236 students that studied the unit with these teachers and took the unit pre- and post-test.

Table 2  
Example part of category system used for deductive coding of ideas.

Variable	Definition	Anchor Example	Borderline Cases
Transfer	S talks about energy being transferred from one system (including fields and objects) to another.	<i>"The fire is transferring energy up to the cup."</i>	Energy has to be transferred from one to another system. Energy only being transferred "from" or "to" something is not sufficient.
Transformation	S talks about one form of energy being transformed into another.	<i>"When the person drops the ball, it [the energy] goes from potential to kinetic energy."</i>	
Interaction	S talks about interactions between objects that are characterized by pushing / pulling.	<i>"this boy is pushing a barrel up a hill"</i>	This includes friction and changes in shape.
Gravity	S talks about gravity pulling something down.	<i>"Because gravity is trying to force it down."</i>	

We used a second rater to conduct an inter-rater reliability analysis in which we found very good agreement (Cohen's Kappa  $\kappa = 0.85$ , (Landis & Koch, 1977)) and after an analysis of the conflicting codes, we were able to resolve them.

**NETWORK ANALYSIS.** The codes resulting from qualitative content analysis provide us with a list of ideas that co-occur in each explanatory account of each phenomenon for each student. Our central assumption for constructing networks is that ideas that co-occur in the explanatory account of a phenomenon are connected. We combined networks across all phenomena the student explained to construct an individual-level network for each student. Further, aggregating across individual-level networks gives networks for the interview sample as a whole for pre and post. We used the network measure of degree to investigate the role of single ideas in students' networks and the network measure of coherence to investigate students' levels of knowledge integration. For our calculations we used the *igraph* (Csardi & Nepusz, 2006) and *tnet* (Opsahl, 2009) packages in R (R Development Core Team, 2008).

**ASSESSING KNOWLEDGE INTEGRATION.** To investigate how our network analytical approach compares to the existing approaches to measure how students connect ideas based on a priori defined linking ideas as in e.g., Lee & Liu (2010), we adopted the knowledge integration scoring scheme used by Lee & Liu (2010) to the phenomena used in our study. Figure 5 shows an example rubric for the bouncing ball phenomenon.

We assigned each phenomenon a knowledge integration score based on the rubric and averaged across the phenomena to come up with a knowledge integration score for each student. We used a second rater to conduct an inter-rater reliability analysis on 16 randomly chosen explanatory accounts (representing 10% of the explanatory accounts) and found substantial agreement (Cohen's Kappa  $\kappa = 0.83$ , (Landis & Koch, 1977)).

Knowledge Integration level	Criteria	Examples
<b>Irrelevant:</b> Off-task	Elicited unrelated ideas.	-
<b>No-link:</b> Non-normative ideas	Elicited non-normative ideas.	<i>“Well, when it falls it biunces up but it’s like, it’s slowly stopping.”</i>
<b>Partial-link:</b> Normative ideas	Elicited any one idea stated.	<i>„Well, it's getting pulled down by the gravity and it's bouncing up 'cause of the material it's made of.“</i>
<b>Full-link:</b> Single link between two normative ideas	Used any of the links stated.	<i>„When it hits like the ground it transfers the energy to the ground.“</i>
<b>Complex-link:</b> Two or more links among three or more normative ideas	Used any of the links stated and added an additional idea or link.	<i>“As it drops, the gravity pulls it down. Every time the ball drops energy is transferred a little bit into the floor and the surroundings.”</i>

### Bouncing ball

Ideas:

- Energy: 1) kinetic energy, 2) potential energy, 3) thermal energy
- Fields: 1) fields between the atoms, 2) gravitational field
- Force: 1) gravity pulls the ball down
- Particles: 1) the ball hits against air particles, 2) the ball is made up of particles
- Temperature: 1) the temperature of the ball / floor / air increases

Links:

- Energy transfer link: 1) energy is transferred to / from the gravitational field from / to the ball, 2) energy is transferred to / from the field between the atoms of the ball from / to the ball, 3) energy is transferred from the ball to the ground / air (surroundings)
- Energy transformation link: 1) kinetic energy is transformed into potential energy and vice versa, 2) kinetic energy is transformed into thermal energy, 3) kinetic energy is transformed into elastic energy and vice versa
- Energy degradation link: 1) energy is transferred from the ball to the environment

Figure 5. Knowledge integration rubric for bouncing ball phenomenon based on Lee & Liu (2010).

## RESULTS

### ***RQ1: OVER THE COURSE OF INSTRUCTION, HOW IS THE CHANGE IN STUDENTS' INTEGRATED KNOWLEDGE AS MEASURED BY A NETWORK ANALYTICAL APPROACH RELATED TO THE CHANGE IN STUDENTS' KNOWLEDGE-IN-USE?***

During instruction, coherence (which is measured across phenomena) of students individual networks increased significantly ( $t(6.82) = 30.24$ ,  $p < 0.001$ ) from pre to post (Figure 6).

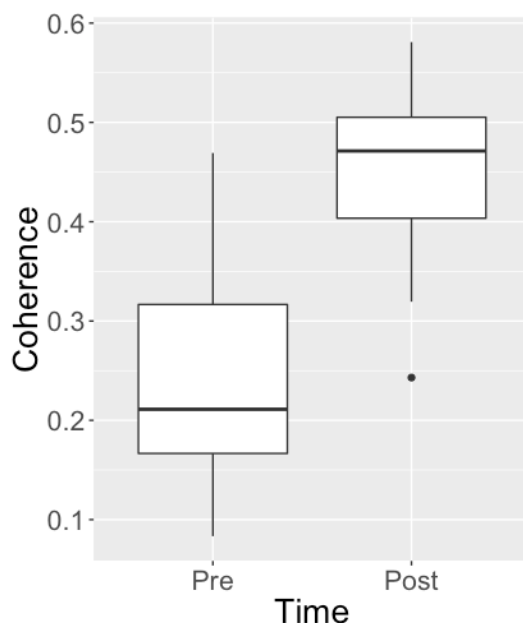


Figure 6. Network coherence for pre- and post-networks of individual students.

To explore to what extent a change in students integrated knowledge as measured by coherence is related to the change in students' knowledge-in-use, we used a linear model to estimate how strongly the change in coherence is related to the change in students' performance on the knowledge-in-use energy assessments. To compare the network analytical approach to existing approaches to measuring how students connect ideas, we also modelled the gain in the knowledge-in-use assessments using the Lee & Liu (2010) based knowledge integration measure. Table 3 shows the mean and standard deviations of the coherence measure, knowledge integration measure, and the knowledge-in-use assessments. The results of the models predicting the gain in the knowledge-in-use assessments from the gain in the coherence measure and the gain in the knowledge integration measure is presented in Table 4.

Table 3

*Mean and standard deviations of the network measure, knowledge integration measures, and knowledge-in-use assessments.*

Variable	M	SD
Knowledge-in-use assessments gain	0.22	0.61
Network Coherence gain	0.25	0.16
Knowledge integration measure gain	1.73	0.65

An increase in one standard deviation in coherence gain maps onto an increase of .55 ( $p = .022$ ) standard deviations in the gain on the knowledge-in-use energy assessment. The model explains roughly a third of the variance in students' gain from pre to post ( $R^2 = .3$ ). Similar results hold for the regression model calculated with the measure of knowledge integration adapted from Lee & Liu (2010).

Table 4  
*Regression models predicting knowledge-in-use gain.*

Model	$\beta^2$	p	$R^2$
Knowledge-in-Use gain ~ network coherence gain	0.55	.022	.30
Knowledge-in-Use gain ~ knowledge integration gain (based on Lee & Liu (2010))	0.41	.05	.23

To further investigate the validity of the network analytical measure, we compared the initial answers to the four scenarios from the post interviews. Table 5 contrasts the initial student answers that led to above median (coherence = 0.55) and below median (coherence = 0.37) coherence networks from the post interviews in Figure 7.

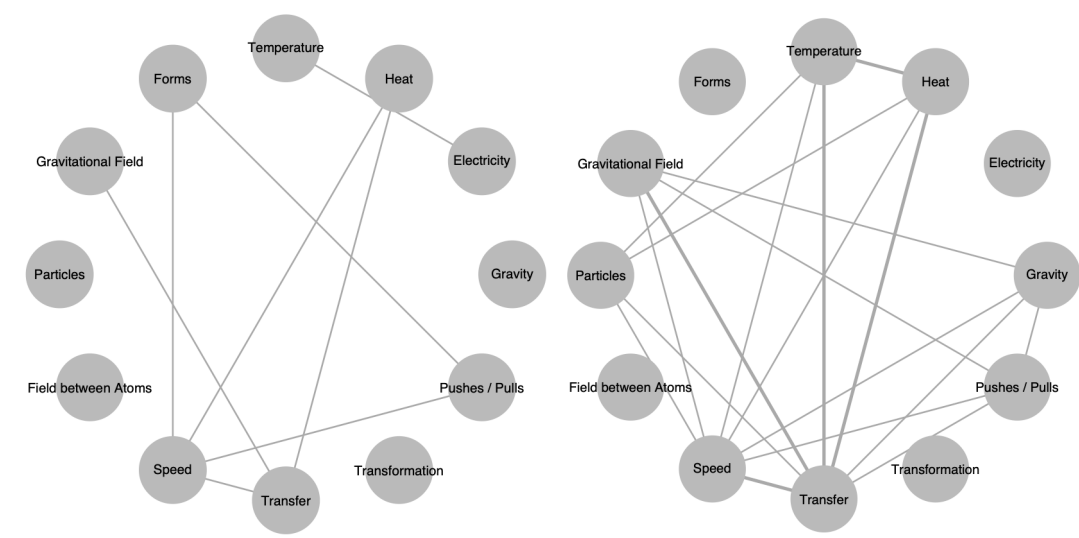


Figure 7. Post-networks of individual students, low coherence left, high coherence right.



Table 5

Initial student answers to the four scenarios from a below median coherence student and above median coherence student (based on post interviews). Usage of "Transfer" ideas printed bold.

Scenario	Below median coherence student answers	Above median coherence student answers
Spinning cup	Well, when someone put the sterno candle under the cup, the cup started spinning because the heat transferred energy to the cup and the air passes through the holes. They are in a certain direction so that's how it spins.	Well, that's a chemical reaction. Burning is always chemical reaction and then the <b>energy transfers</b> from the flame through the air molecules into the cup and then the air molecules go out the hole in the cup and it causes the cup to get a speed increase and spin.
Bouncing ball	The person drops the ball and it bounces back up but every time it bounces back up <b>it loses more and more energy to the field.</b>	When he has the ball up here the gravitational field has the energy stored and then he drops it, it gives it back but it can't go back higher because the... isn't something to do with how the gravitational field, like it, each time it goes the surroundings so it's losing just a tad bit of energy each time to the surroundings so it can't bounce back to the same height. When he drops the ball <b>the energy goes from the field to the ball</b> and some of it goes to like the air.
Pushing a barrel up a ramp	Well, the person is pushing it and it's spinning and going up.	Well you could say <b>the kid gives the barrel energy</b> by pushing on it and then the speed increase for the barrel.
Electric heater	The person turned on the knob and it got hotter because there's a cord that's plugged into an outlet and that outlet gives the machine, it gives it fuel to be able to be heated up when it turned on.	Well there's like a little box some I'm guessing <b>energy transfers from inside the box to the each one of those wires</b> and then the heat waves cause it to heat up because there's no such thing as warm energy or cold energy. So the energy transfers to the ... whatever those are and then they start to heat up more and more.

The above median coherence student uses the idea of energy transfer across all four scenarios while the below median coherence student uses the idea only once. The above median student also uses a broader range of ideas together with energy transfer, e.g., in the explanation of the bouncing ball, the high coherence student elaborates in a more detailed fashion how energy is transferred away from the bouncing ball. Thus, the coherence measure

reflects differences in the extent to which students connect a set of core ideas across phenomena.

In sum, we found a strong relationship between the change in students' knowledge-in-use and the change in students' network coherence. We found a similar relationship using a measure of knowledge integration based on Lee & Liu (2010). Together with the fact that differences in network coherence between students are reflected in the extent to which they consistently use ideas across phenomena, this lends validity to the network analytical measure of coherence.

***RQ2: WHAT QUALITATIVE INFORMATION ABOUT STUDENTS' KNOWLEDGE NETWORKS DOES THE NETWORK ANALYTICAL APPROACH PROVIDE AND HOW IS THIS RELATED TO STUDENTS' KNOWLEDGE-IN-USE?***

***PRE/POST INDIVIDUAL DEVELOPMENT.*** Figure 8 shows an individual student's networks for pre and post whose gain from pre to post on the knowledge-in-use assessments is representative for the average of the interview sample.



Figure 8. Pre (left) and post (right) network of an individual student.

Visual inspection readily reveals differences between the two networks. Prior to instruction, the student only connects "Electricity" with "Temperature" and "Gravity" with "Pushes / Pulls". The first connection comes

from the electric heater scenario, *"I see like electricity flowing through like the wires, well, I guess like the things to heat up a room. I don't ... I don't really know"*. The second is made in the bouncing ball scenario, *"Uhm, I would explain it like uhm the kid's putting pressure on it to keep it up even if the gravity wants to ... to pull it back down."* The third connection comes in the person pushing a barrel up a ramp scenario, *"Eh, because the friction, I guess, is pulling it down. Yeah, and like gravity."* The pre-network corresponds to a network coherence of 0.09. The post-network, however, shows more connections between a broader range of ideas, corresponding to a network coherence of 0.46. "Transfer" is the best-connected idea in the network with a degree of six and consistently used across scenarios to connect other ideas. In the electric heater scenario "Electricity" is now connected to the idea of "Temperature" via "Transfer": *"I saw... uh, heat like, well, no, I don't really see heat, but like the strings I guess you call it I don't know, uh they heated up once he turned the dial and mostly they do that because there's like probably a battery inside of it and once you turn that ... energy transfers to those and then those transfer like heat out, I don't know"*. Similarly, the student consistently uses "Transfer" across the person pushing a barrel up a ramp and the bouncing ball scenario and connects it to range of other ideas such as "Speed" or "Temperature": *"Uh the boy is transferring energy to the barrel to make it go up."* *"I saw the guy drop the basketball onto the ground and then it not bounce back up not to its original height and that happens because energy is being transferred to the ground. As it falls the ball hits that and it transfers energy to the ground and the surroundings and then it makes the temperature increase."* The change in how the student only connects few ideas before the unit and connects various ideas and consistently uses "Transfer" across scenarios after the unit is captured in the notable increase in integration as measured by network coherence (0.09 to 0.46) and degree of the "Transfer" idea (0 to 6).

**AGGREGATED PRE/POST DEVELOPMENT.** The change in students' knowledge structure over the course of the unit is most vividly apparent in Figure 9 which shows aggregated networks for pre-and post.

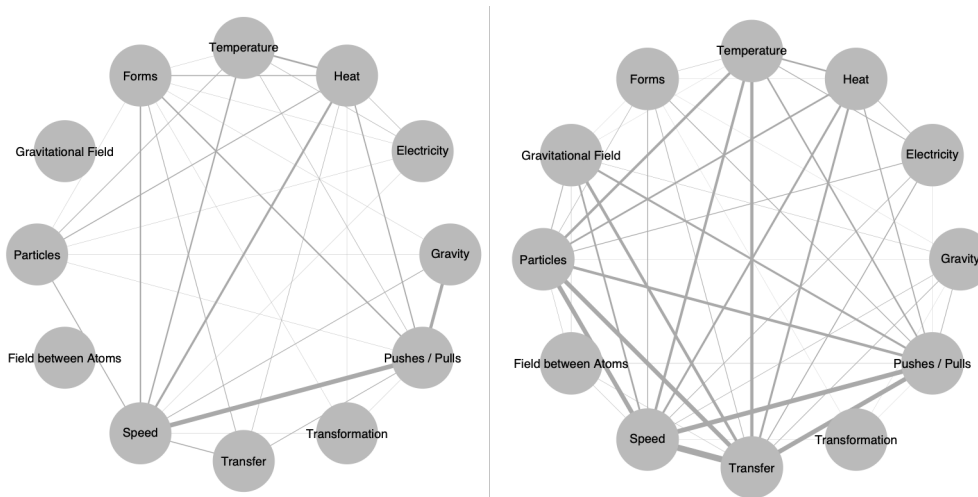


Figure 9. Aggregated network representation of co-occurrences of student ideas, pre (left) and post (right). Line thickness represents number of co-occurrences.

Although no individual student network is identical to these aggregated networks, they reflect the central tendencies: we see a strong increase in degree (the number of other ideas an idea is connected to) for "Transfer", "Gravitational Field", and "Field between Atoms" – all ideas emphasized in the unit. Further, "Transfer" has the strongest degree in the post-network. Lastly, "Forms" and "Transformation" - energy ideas that are not emphasized in the unit – do not change in degree and have relatively low degree. The diagrams in Figure 9 suggest that during instruction, students developed more well-connected ideas about energy and that the concept of transfer gained a more prominent role as an idea that students activated.

**CONNECTING QUANTITATIVE FEATURES OF STUDENTS' KNOWLEDGE NETWORKS TO STUDENTS' KNOWLEDGE-IN-USE.** In the background section, we have argued that the degree measure allows to determine the relative importance of ideas in students' knowledge structures, i.e., the ability to identify linking-ideas empirically. To do so, we considered the top five ideas with highest degree in students aggregated post-instruction networks, i.e., the best-connected ideas, and investigated to what extent an increase in connections of these ideas from pre to post (as it should occur during learning) predicted student learning. The results of the five regression models are presented in Table 6.

Table 6

*Standardized regression coefficient  $\beta^2$ , p-value, variance explained  $R^2$ , F-test, and information criterion AIC for five regression models in which students' learning gain on the energy pre/post-test was predicted by the gain in degree of the respective idea listed in the table.*

Idea	$\beta^2$	p	$R^2$	AIC
Transfer	0.49	.046	.24	48.57
Pushes / Pulls	0.37	.150	.13	50.76
Speed	0.44	.080	.19	49.63
Forms	0.39	.125	.15	50.46
Particles	0.19	.476	.03	52.62

We found the standardized regression coefficient of degree gain for "Transfer" to be the largest (0.49). Only the effect of "Speed" comes close which, however, is only approaching statistical significance, explains less variance, and has a higher AIC. "Pushes / Pulls" and "Forms" which together with "Transfer" would be natural candidates for linking-ideas from a theoretical perspective, explain about 10% less variance than "Transfer" and have higher AIC. Further, their effects are about 0.1 smaller and not statistically significant. In general, evaluating the models by their ability to explain the data  $R^2$  and accuracy AIC, "Transfer" is the best predictor as it has the highest  $R^2$  and lowest AIC of the five. This means that the increase in connections between energy transfer and other ideas in students' idea networks is more strongly related to students' performance on a distal knowledge-in-use assessment than the other high-degree ideas.

In sum, visualizing the networks gives qualitative insights into students' knowledge networks. In addition, derived quantitative measures allow to identify core ideas in students' knowledge networks.

## DISCUSSION

The premise of the many current standards documents emphasis on a small set of powerful science ideas, such as the US Framework for K-12 Science Education (National Research Council, 2012) or the German Bildungsstandards (Sekretariat der ständigen Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland, 2004), is that having a well-developed knowledge base organized around major ideas of a domain is the basis of scientific literacy (Bransford, 2000). Further, emphasizing these major

ideas (e.g., “disciplinary core ideas” in the NGSS and “Basiskonzepte” (basic concepts) in the Bildungsstandards) is supposed to help students develop such organized knowledge. In the domain of energy for example, increasingly connected knowledge networks around central energy ideas should be positively associated with students’ ability to make sense of phenomena using energy ideas (Bransford, 2000; Chi et al., 1981; Linn, 2006). We have developed a ground-up approach that provides qualitative and quantitative information about students’ ability to activate and connect sets of relevant ideas as they make sense of phenomena across contexts, i.e., students’ integrated knowledge. We found that students linked ideas around the central idea of energy transfer (which serves as a disciplinary core-idea in middle school and was emphasized in the energy unit in which the students participated) and that students that did so to a larger extent, performed better on a knowledge-in-use assessment in which students had to connect scientific practices and energy ideas. This supports the premise of the Framework for K-12 Science Education or the Bildungsstandards of deep learning around a small set of core ideas. In addition, our results support theoretical work that suggests that energy transfer can be a particularly helpful energy idea to make sense of phenomena (Brewer, 2011; Ellse, 1988; Nordine et al., 2019; Quinn, 2014; Swackhamer, 2005).

Current approaches to measuring how students connect ideas often (e.g., Kauertz & Fischer (2006) or Lee & Liu (2010)) define linking-ideas a priori. In general, as our approach is more open in the sense that it does not rely on a priori established linking-ideas, it enables a more full and flexible description of students’ ideas without filtering through a pre-defined rubric (Steedle & Shavelson, 2009). This appears especially valuable when it is not really clear or at least contested which ideas should be considered central and how students’ ideas develop. For example, in domains with multiple core ideas such as energy it is not necessarily clear which possible linking ideas (energy transfer, energy transformation) are most productive (Papadouris & Constantinou, 2016). The degree measure can help to resolve such issues.

Further, our results extend work that has linked how students connect ideas with their performance on related MC assessments (Kauertz & Fischer, 2006; Lee & Liu, 2010; Nordine et al., 2011) as we used knowledge-in-use assessments in which students had to connect disciplinary ideas with scientific practices and cross-cutting concepts. In general, the relationship of scientific practices, disciplinary core ideas, and cross-cutting concepts is not well defined when those components are integrated in knowledge-in-use performances. Our results provide a first step towards better understanding the role of well-organized disciplinary knowledge for knowledge-in-use, as the coherence measure that is insensitive to elements of a scientific practice, explained a large share of the variance in students' knowledge-in-use.

### ***LIMITATIONS***

The network analysis method we present in this paper is built on the assumption that we consider ideas connected if they co-occur. Thus, we do not differentiate between students that meaningfully connect e.g., "force" with "friction" and those that use both ideas within the same explanatory account in isolation. However, the premise of the present approach is probabilistic as it assumes that given a sufficient number of phenomena, ideas that co-occur repeatedly, do so because they are connected meaningfully. Network coherence as a measure of integrated knowledge does not describe a single students' explanation of a phenomenon but describes a student's idea network given multiple explanations of phenomena from the student. Further, we ignore the order in which ideas are presented. Thus, we cannot differentiate between students that start their explanatory account with deep conceptual ideas such "transfer" and then use surface level ideas such as "speed" and those that start with surface level ideas and then go on to more conceptual ones. While future network approaches could at least in principle consider the order in which ideas are presented, it is also questionable to what extent order is a relevant feature of idea networks and not feature of language or other cognitive processes, given the prominent role of parallel processing theories in cognitive science (Rumelhart & McClelland, 1986).

In sum, we consider that interpreting co-occurrence as connection and ignoring order are helpful in balancing the simplicity of assumptions and their effectiveness in practice which these two assumptions have already demonstrated in the contexts of automated semantic analysis (Blei, 2012; Landauer, 2014; Zehner, Sälzer, & Goldhammer, 2016).

### **IMPLICATIONS & FUTURE DIRECTIONS**

Our approach provides qualitative and quantitative information about students' integrated knowledge which can be linked to students' knowledge-in-use while not relying on a priori defined linking ideas. Thus, it allows researchers fuller access to the complexity of conceptual development and growth in understanding over time and addresses the problem, that developmental pathways may remain hidden due to the filtering through pre-defined learning progressions (Duncan & Rivet, 2013). Given the promising results we presented, we consider future research that uses the approach and helps to further develop and refine it warranted.

Our approach is built ground-up from the ideas that students activate. This should not only help to avoid filtering through pre-defined learning progressions but also help to reveal intermediary stages in the developments of students' knowledge networks where students might only be able to activate ideas, but not to connect them. This finer grain size could for example inform the discussion in the energy literature about the influence of developmental stages for energy learning progressions (X. Liu & McKeough, 2005).

Our method focused on the normative part of students' knowledge networks. Future research could extend the approach to include non-normative ideas to better understand the role that they play in students' knowledge networks and how they develop over time. In the domain of energy for example, there is a rich literature on student conceptions of energy (Duit, 2014; Watts, 1983) but the extent to which they impair or may even enhance (as



productive intermediary stages) how students develop well-organized knowledge networks is little researched.

Further, what we have sketched here for the domain of energy is in principle applicable to other domains and core-ideas like force or evolution in biology.

Apart from such research oriented outcomes, our network analytical approach has the potential to provide rich diagnostic information for teachers and curriculum developers that current assessments do seldomly provide (Duncan & Hmelo-Silver, 2009). However, to be applicable in wide spread practice, one would have to find a way to scale the approach, possibly using automation techniques inspired by the field of learning analytics.

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## **PUBLICATION IV: DER SYSTEM TRANSFER ANSATZ**

### **ABSTRACT**

Das Basiskonzept Energie stellt für viele Schülerinnen und Schüler eine Herausforderung dar. Besonders die Energieerhaltung und potentielle Energie bereiten Lernenden Probleme. Wir stellen eine Unterrichtssequenz vor, die auf Energietransfers fokussiert und erörtern, wie diese Verständnisschwierigkeiten begegnen kann.

## **EINLEITUNG**

Energie ist ein Basiskonzept im Physikunterricht. Allerdings stellt das Energiekonzept für viele Schülerinnen und Schüler eine Herausforderung dar [1]. Dies beginnt z.B. bei der Energieform der potentiellen Energie, die für Schülerinnen und Schüler schwer greif- und lokalisierbar ist. Auch der für das Energiekonzept zentrale Aspekt der Energieerhaltung bereitet Schülerinnen und Schülern Probleme. Die Energieerhaltung in (im Unterricht häufig behandelten) geschlossenen Systemen deckt sich nicht mit den Alltagserfahrungen der Schülerinnen und Schüler mit dissipativen Prozessen (Warum muss ich mein Handy aufladen, wenn Energie doch erhalten ist?). Aus diesem Grund haben sie oft Schwierigkeiten das Konzept der Energieerhaltung konsistent bei verschiedenen Phänomenen, durch Fächer und Klassenstufen hinweg als Strategie einzusetzen. Als Folge entwickeln nur wenige Schülerinnen und Schüler ein adäquates Energieverständnis [2]. Damit fehlt den Schülerinnen und Schülern ein wichtiges Analysewerkzeug der Naturwissenschaften.

Als mögliche Lösung dieser Probleme wurde in der Literatur an verschiedenen Stellen diskutiert mehr auf den Transfer von Energie und weniger auf die Transformation von Energie zu fokussieren (siehe z.B. [3]). Das Leitprinzip eines solchen System-Transfer Ansatzes lautet: In jedem Phänomen wird Energie zwischen interagierenden Systemen transferiert. Dabei laufen in den Systemen Prozesse ab, bei denen Energie zu- oder abnimmt (Abb. 1).

### **Leitprinzip des System-Transfer Ansatzes**

In jedem Phänomen wird Energie zwischen interagierenden Systemen transferiert. Dabei laufen in den Systemen Prozesse ab, bei denen Energie zu- oder abnimmt.

Um Phänomene zu erklären, muss man sich folgende Fragen stellen:

Welche Systeme sind beteiligt?

Welche Prozesse laufen in diesen Systemen ab?

Welche Energietransfers resultieren daraus?



### Systeme, Prozesse, Energietransfer

Systeme: Systeme sind definierte Objekte in welche Energie hinein und heraus transferiert werden kann.

Prozesse: Messbare Prozesse, die in Systemen ablaufen und bei denen sich die Energie im System entweder verringert oder vergrößert.

Energietransfer: Energietransfers finden zwischen wechselwirkenden Systemen statt. Die Richtung hängt von den in den Systemen ablaufenden Prozessen ab.



Abb. 1: Allgemeines Schema des System-Transfer Ansatzes.

Bei der Umsetzung des System-Transfer Ansatzes im Unterricht würde man aber z.B. mit dem Systembegriff Schwierigkeiten erwarten. Im Folgenden stellen wir erprobte Aktivitäten vor um die zentralen Konzepte des System-Transfer Ansatzes in der Mittelstufe einzuführen, zu motivieren und Lernschwierigkeiten zu begegnen. Zum Abschluss zeigen wir an Ausschnitten eines Unterrichtsgesprächs wie Schülerinnen und Schüler sich mit Hilfe des System-Transfer Ansatzes dissipative Phänomene aus dem Alltag erklären können.

### SYSTEME

Wie unterrichtet man Systeme in der Mittelstufe? Der Systembegriff erscheint zunächst komplex. Im Rahmen unserer Unterrichtseinheit stellen aber häufig schon ein Objekt oder eine kleine Ansammlung von Objekten ein System dar. Entscheidend ist, dass diese interagieren, also z.B. kollidieren. Wenn Schülerinnen und Schüler ein Phänomen betrachten, müssen sie also entscheiden können, welche Objekte miteinander interagieren. Zu Beginn der

Unterrichtseinheit zeigen wir Schülerinnen und Schülern ein Radiometer (Abb. 2) und geben ihnen Gelegenheit mit diesem und einer Taschenlampe zu experimentieren. Beleuchtet man das Radiometer mit der Taschenlampe, beginnt dieses sich zu drehen. Ändern die Schülerinnen und Schüler nun die Helligkeit der Taschenlampe (bei gleichzeitigem konstant Halten des Abstandes zwischen Taschenlampe und Radiometer) ändert sich Rotationsgeschwindigkeit des Radiometers. Als interagierende Komponenten lassen sich hierbei folglich die Taschenlampe und das Radiometer ausmachen. Der Prozess des „Leuchtens“ in der Taschenlampe bedingt den Prozess des „Drehens“ im Radiometer. Hieran nicht beteiligt und somit nicht Teil der Systeme ist z.B. der Tisch auf dem das Radiometer steht oder die Person, die die Lampe bedient.

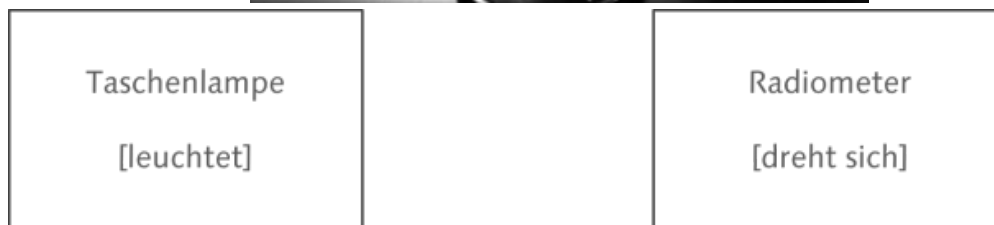


Abb. 2: Radiometer. Darunter eine einfache Repräsentation um die Systeme und die darin ablaufenden Prozesse darzustellen.

Als weiteres Phänomen wird den Schülerinnen und Schülern ein Heronsball vorgeführt (Abb. 3). In diesem Aufbau stellt die Getränkedose den Heronsball dar. In der Dose befindet sich Wasser. Der unter der Dose positionierte Brenner lässt das Wasser Verdampfen. Der Wasserdampf strömt dann durch zwei im oberen Bereich der Dose und in entgegengesetzte Richtung zeigende Löcher aus der Dose. Dies versetzt die Dose in Rotation. Variiert man nun in diesem Demonstrationsversuch die Intensität des Brenners, rotiert die Dose entsprechend schneller oder langsamer. Als interagierende Systeme

ergeben sich hier für die Schüler also die Dose sowie der Brenner. In diesen laufen die Prozesse „dreht sich“ bzw. „brennt“ ab. Andere Objekte wie z.B. das Stativmaterial interagieren hier nicht und sind somit nicht Teil der Systeme.

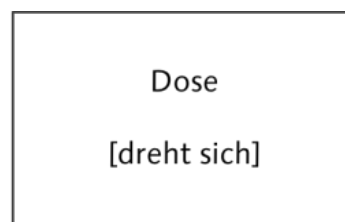
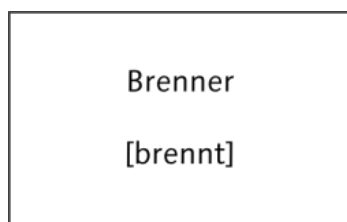


Abb. 3: Heronsball und Repräsentation der Systeme und der in ihnen ablaufenden Prozesse.

### ENERGIETRANSFER

Wie motiviert man nun die Idee, dass Energie zwischen interagierenden Systemen transferiert wird? Betrachten wir noch einmal die beiden Phänomene Radiometer und Heronsball. Für sich gesehen, scheint beim Radiometer das Leuchten der Taschenlampe die Ursache für die Rotation des Radiometers zu sein und beim Heronsball das Brennen der Flamme die Ursache für die Rotation der Getränkedose. Die Mechanismen sind hierbei offensichtlich unterschiedlich (Licht beim Radiometer bzw. Wärme beim Heronsball). Gemeinsam ist beiden Phänomenen aber, dass ein Prozess in einem System (Leuchten bei der Taschenlampe bzw. Brennen beim Brenner) im anderen System eine Rotationsbewegung auslöst. Wie lässt sich hierfür eine gemeinsame Beschreibungsebene finden? Die Antwort ist *Energietransfer*. Um beide

Phänomene mit denselben Konzepten zu erklären, wird der Begriff der Energie eingeführt. Diese kann zwischen interagierenden Systemen transferiert werden. Die Rotation des Radiometers sowie der Getränkedose lässt sich durch einen Energietransfer aus dem jeweils anderen System (Taschenlampe bzw. Brenner) erklären.

Dieses grundlegende Schema wird in der Unterrichtseinheit nun an diversen Phänomenen mit verschiedenen Transfermechanismen durchgespielt. Hierbei wird jeweils besprochen, wie die Richtung der Energietransfers mit den in den Systemen ablaufenden Prozessen zusammenhängt. Außerdem wird die qualitative Energieerhaltung dadurch eingeführt, dass die mit dem Energietransfer verbundenen Prozesse immer ausgeglichen sein müssen, d.h. es ist nicht möglich, dass die Energie in allen System zu- oder abnimmt. Ein Beispiel hierfür sind Kollisionen. Kollidiert ein Wagen (A) mit einem zweiten Wagen (B), welcher sich in Ruhe befindet, beobachtet man wie Wagen (A) langsamer wird und Wagen (B) beschleunigt (Abb. 4).

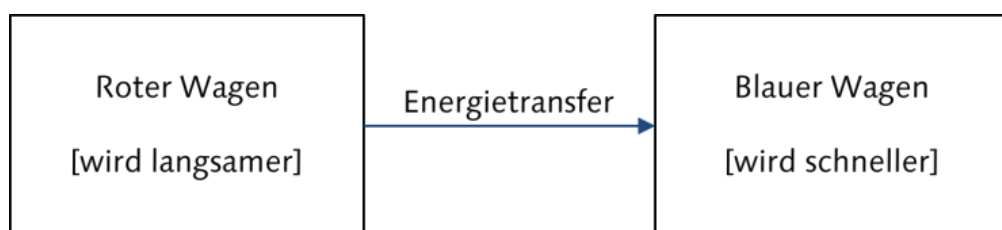
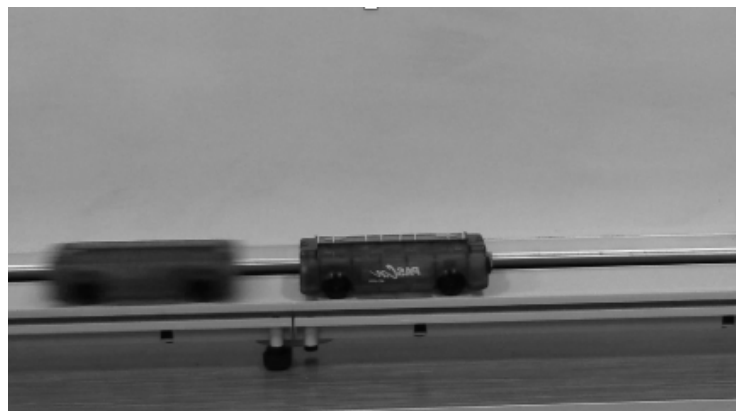


Abb. 4: Kollidierende Wagen. Darunter eine Repräsentation die die Systeme (Kästen), die in ihnen ablaufenden Prozesse (eckige Klammern), sowie die Richtung des Energietransfers (Pfeil) darstellt.

Die Systeme sind hierbei Wagen (A) und Wagen (B) in welche die Prozesse „wird langsamer“ und „wird schneller“ ablaufen. Die Schülerinnen und Schüler wissen vom Radiometer und Heronsball, dass der Beginn einer Bewegung (eine Beschleunigung) mit einem Energietransfer in das System verbunden ist. Hier können die Schülerinnen und Schüler sich erarbeiten, dass eine Zunahme der Energie in einem System („wird schneller“) mit einer Abnahme der Energie im anderen System („wird langsamer“) einhergeht. Die Energie kann also nicht in allen Systemen zu- oder abnehmen. So wird die qualitative Energieerhaltung deutlich.

In den ersten Stunden der Unterrichtseinheit werden also der Systembegriff sowie das Konzept des Energietransfers (inkl. qualitativer Energieerhaltung) eingeführt und von den Schülerinnen und Schülern konsistent zur Erklärung einer Reihe von Phänomenen angewendet. Soweit erscheint der System-Transfer Ansatz unproblematisch. Was ist aber mit Phänomenen, die klassischerweise mit *Energieumwandlungen* in einem System beschrieben werden wie z.B. einer Batterie wo chemische in elektrische Energie umgewandelt wird? Solche Fälle haben gemeinsam, dass die Energieform, die umgewandelt wird, letztlich eine Form der potentiellen Energie ist. Diese stellt für Schülerinnen und Schüler ohnehin häufig eine Herausforderung dar, da sie anders als z.B. kinetische Energie nicht einem Objekt zugeschrieben werden kann, sondern von der relativen Position mindestens zweier Objekte abhängt. Für Schülerinnen und Schüler ist die Lokalisierung der potentiellen Energie schwierig. Die potentielle Energie eines z.B. fallenden Balls scheint von der Höhe des Balls abhängig. Schülerinnen und Schüler assoziieren deshalb häufig die potentielle Energie mit dem Ball alleine. Der Sprachgebrauch „der Ball hat potentielle Energie“ kann dies noch verstärken. Wie behandelt also der System-Transfer Ansatz die potentielle Energie? Im System-Transfer Ansatz würde die Assoziation der potentiellen Energie mit dem Ball zu dem Problem führen, dass das System „Ball“ Energie zu sich selbst transferieren müsste. Schließlich wird das System Ball schneller. Man benötigt also ein weiteres System. Hierzu führt man nun das Konzept des Feldes ein. Dieses löst einerseits Problem das Transfers zu sich selbst und lokalisiert die Energie für die

Schülerinnen und Schüler. Im nächsten Abschnitt zeigen wir die Aktivität, mit der der Feldbegriff in der Unterrichtseinheit eingeführt wird.

## FELDER

Da wir uns in der Mittelstufe befinden, ist das Unterrichtsziel, einen anschlussfähigen Feldbegriff für die Schülerinnen und Schüler zu etablieren. Zentral ist hierbei, dass Felder als Systeme in die Energie hinein- oder hinaus-transferiert werden kann und als real existierend gesehen werden. Diese Eigenschaften werden den Schülerinnen und Schülern im Verlauf von zwei Aktivitäten exemplarisch an Magnetfeldern vermittelt.

Zuerst wird den Schülerinnen und Schülern folgendes Phänomen vorgeführt: In Abb. 5 sieht man zwei Wagen auf einer Schiene. Auf den Wagen sind Magnete so ausgerichtet, dass die Wagen sich abstoßen. Lässt man die Wagen nun los, beschleunigen beide und entfernen sich voneinander. Nun wird versucht das Phänomen mit den Schülerinnen und Schülern im System-Transfer Ansatz zu erklären: Zwei Wagen beschleunigen. Diese Prozesse zeigen, dass die Energie in den Systemen zunehmen muss. Im Unterrichtsgespräch sollte deutlich werden, dass dies gegen den zuvor erarbeiteten Grundsatz „Die Energie kann nicht in allen System zu- oder abnehmen.“ verstößt. Folglich muss es noch ein weiteres System geben, aus dem die Energie transferiert wird. Im Unterrichtsgespräch stellt sich also die Frage, welches dieses System sein könnte.

Als mögliche Systeme werden die Magnete genannt. Nun wird den Schülerinnen und Schülern mit Hilfe von Eisenspänen oder falls vorhanden einem Ferrofluid das Magnetfeld eines Magneten sichtbar gemacht. Wird nun ein zweiter Magnet in die Nähe des ersten gebracht, können die Schülerinnen und Schüler sehen, wie sich die Form des Feldes verändert. Der Grad der Verformung des Magnetfeldes hängt hierbei vom Abstand der zwei Magneten ab. Dies kann entweder durch Demonstration oder im Schülerexperiment verdeutlicht werden.

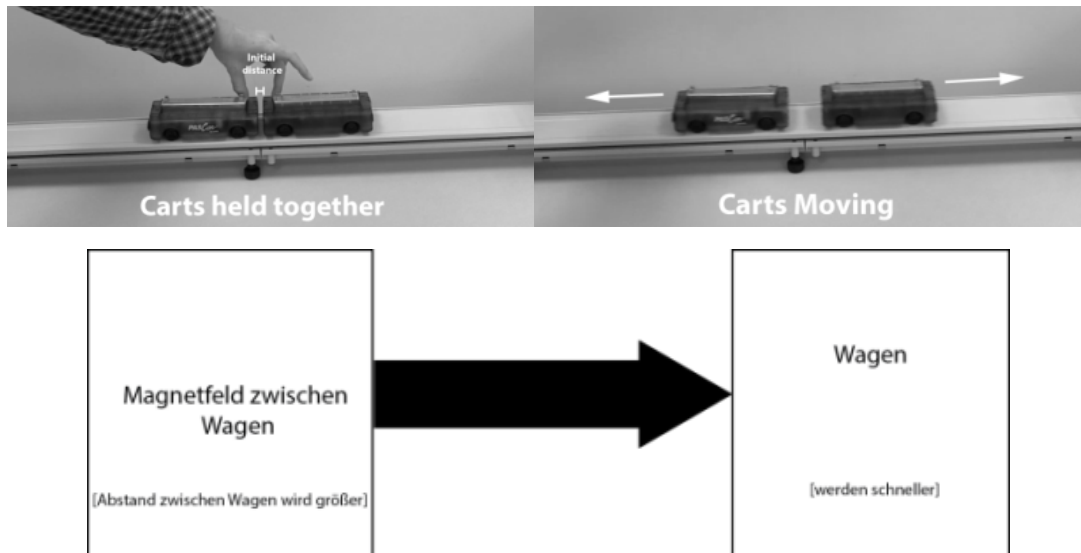


Abb. 5: Links: Zwei Magnetwagen auf einer Schiene. Mitte: Zwei Magnetwagen beschleunigen in entgegengesetzte Richtung. Rechts: Eine Repräsentation des Phänomens.

Nun wird die Diskussion über die Erklärung der beschleunigenden Wagen fortgesetzt. Die die Schülerinnen und Schüler sind jetzt in der Lage die Antwort Magnetfeld selbst zu finden. Das Magnetfeld als System erklärt an dieser Stelle die sonst wundersame Beschleunigung der beiden Wagen. Das Konzept Feld wird erklärungsmächtig.

An dieser Stelle lässt sich außerdem das Konzept System noch einmal diskutieren. Es gibt die Möglichkeit beide Wagen als einzelne Systeme zu betrachten zu denen Energie vom magnetischen Feld transferiert wird oder aber sie zu einem System zusammenzufassen, da die Wagen den gleichen Prozessen unterliegen.

Ist das Magnetfeld als System, in welches Energie hinein- oder hinaus-transferiert werden kann, etabliert, stellt sich noch die Frage nach dem in diesem ablaufenden Prozess: Die Schülerinnen und Schüler konnten die Verformung des Feldes zwar an Eisenspänen oder Ferrofluid beobachten, allerdings wird diese beim Phänomen der beschleunigenden Wagen nicht sichtbar. Sichtbar ist allerdings, dass sich der Abstand zwischen den Magneten verändert hat. Dass die Verformung mit Änderung des Abstandes zwischen den Magneten verbunden ist, ist von Eisenspänen bzw. Ferrofluid ebenfalls bekannt. Somit wird motiviert, dass als einfach sichtbarer Prozess die

Änderung des Abstandes (näher zusammen / weiter weg) als Prozess des Systems „Magnetfeld“ verwendet wird. Nachdem mit diesen Aktivitäten der Feldbegriff eingeführt ist, lassen sich im weiteren Verlauf der Einheit gravitative oder elektrische Felder analog motivieren und verwenden.

### ENTWERTUNG UND ERHALTUNG

Nachdem wir in den vorangegangenen Abschnitten den Unterrichtsgang an den zentralen Aktivitäten zu Systemen, Energietransfer und Feldern dargelegt haben, wollen wir abschließend zeigen, wie Schülerinnen und Schüler im System-Transfer Ansatz das Energiekonzept konsequent anwenden um sich dissipative Alltagsphänomene zu erschließen. In einer Unterrichtsstunde wurde den Schülerinnen und Schülern folgendes Phänomen präsentiert: Ein Ball rollt über Asphalt, trifft auf Sand, wird dabei langsamer und stoppt schließlich (Abb. 6).

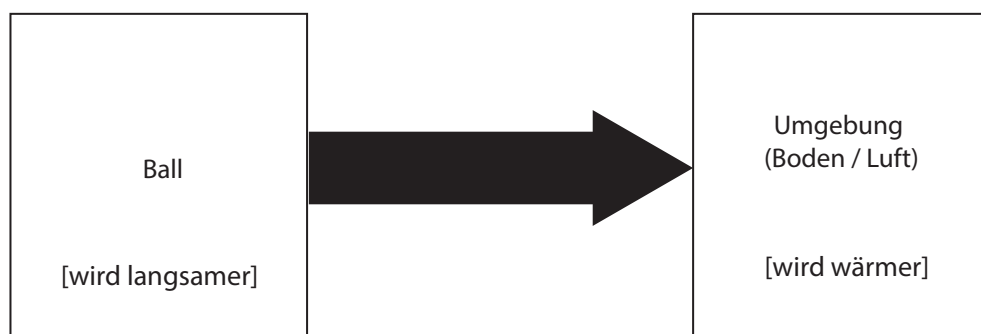


Abb. 6: Ein rollender Ball, der langsamer wird. Daneben eine Repräsentation des Phänomens aus dem System-Transfer Ansatz.



Nun wurden die Schülerinnen und Schüler gebeten, das Phänomen mit Hilfe des Energiekonzepts zu erklären. Es ist klar, dass das System „Ball“ langsamer wird und somit Energie aus ihm weg transferiert wird. *„Schüler: Der Ball wird langsamer und stoppt. Deshalb wird Energie von ihm weg transferiert.“* Nun spekulieren die Schülerinnen und Schüler jedoch, welches das andere Systeme sein könnte, und welcher Prozess in diesem Abläuft. Aufgrund der (qualitativen) Energieerhaltung wissen sie jedoch, dass es ein anderes System geben muss, auch wenn dieses nicht offensichtlich ist: *Schülerin: „Da muss ein anderes System sein. Ich frag mich, was der Sand macht. Er scheint nur den Ball zu stoppen. Also, Ich weiß, dass der Ball langsamer wird. Aber ich frag mich, was der Sand macht.“* Die Schülerinnen und Schüler haben nun die Voraussetzungen um zu dem Schluss zu kommen, dass im System „Sand“ ein Prozess wie „wird wärmer“ oder „wird schneller“ der mit einem Energietransfer in das System „Sand“ verbunden ist, ablaufen muss.

Im späteren Verlauf der Unterrichtseinheit wird für dissipative Prozesse das System „Umgebung“ eingeführt, in welchem der Prozess „wird wärmer“ abläuft. Es ist hierbei klar, dass beim Stoppen von Prozessen die Energie erhalten bleibt, allerdings aus dem primär im Fokus stehenden System (im Beispiel oben der Ball) heraustransferiert wurde. Dies verbindet die Alltagserfahrung der Schülerinnen und Schüler, dass Energie „verbraucht“ wird mit einer physikalisch korrekten Beschreibung des Phänomens.

## **ZUSAMMENFASSUNG**

Energie ist für Schülerinnen und Schüler ein herausforderndes Konzept. So sind z.B. der Begriff der potentiellen Energie aber auch der scheinbare Widerspruch von Dissipation und Energieerhaltung für Schülerinnen und Schüler schwierig. Ein Fokus auf Energietransfers zwischen Systemen (System-Transfer Ansatz) anstatt auf Energietransformationen in Systemen hat das Potential diese Schwierigkeiten zu mindern. Die potentielle Energie wird im System-Transfer Ansatz im Feld lokalisiert. Damit wird potentielle Energie für Schülerinnen und Schüler greifbar ohne Kompromisse bei der fachlichen Darstellung machen zu müssen. Das Stoppen von Prozessen wird mit einem

Energietransfer in ein weiteres System (z.B. System „Umgebung“) verbunden. Dies ist konsistent mit der Alltagswahrnehmung, dass Energie „verbraucht“ wird, aber auch eine physikalisch korrekte Beschreibung dissipativer Prozesse. Bei dieser Art der Beschreibung wird die Energieerhaltung deutlich. Die Konzepte System und Feld sind komplex und können so Schwierigkeiten erzeugen. In diesem Beitrag haben wir anhand zentraler Aktivitäten einer von uns entwickelten und erprobten Unterrichtseinheit auf Basis des System-Transfer Ansatzes gezeigt, wie man diese Schwierigkeiten im Unterricht auflösen kann. Unterricht auf Basis des System-Transfer Ansatzes kann Schülerinnen und Schülern dabei helfen ein Energiekonzept zu entwickeln, welches sie konsistent zur Erklärung von Phänomenen anwenden können.

#### **DANKSAGUNG**

Der hier vorgestellte System-Transfer Ansatz wurde im Rahmen eines internationalen Kooperationsprojekts zur Erforschung von Lerntrajektorien im Energiekonzept entwickelt, dass von der NSF (DUE-1431725) gefördert wird.

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## DISCUSSION

Publications I and III found that students develop knowledge-in-use about energy in the systems-transfer unit. The unit emphasizes the connections between energy, systems, and fields and does not rely on forms. Further, publication III found that students also develop well-organized knowledge networks, that is, integrated knowledge about energy, and that having integrated knowledge is strongly associated with knowledge-in-use. Lastly, publication II found that a representation, the Energy Transfer Model, that serves as a cognitive tool in the systems-transfer unit, supports students in identifying hidden systems and processes in phenomena which leads to new insights. Together, these results support the premise that the features of project-based learning, especially driving questions and the usage of tools, support students in developing an integrated knowledge as a prerequisite for knowledge-in-use. What does this mean for the teaching and learning of energy, the relationship between integrated knowledge and knowledge-in-use, and how instruction can support students in developing the latter?

### A NEW TAKE ON ENERGY LEARNING PROGRESSIONS

The results presented in this dissertation suggest rethinking the current paradigm of the forms-based energy learning progression. The case for the traditional focus on forms is mostly based on the notion that forms are an easy idea to begin talking about energy (Nordine et al., 2019; Quinn, 2014) and that learning progressions appear to go through forms (Herrmann-Abell & DeBoer, 2017; Lee & Liu, 2010; Neumann et al., 2013). However, our findings indicate that students have little trouble to start talking about energy in terms of transfers of energy between systems and are able to successfully track energy in many phenomena, that is, employ qualitative notion of energy conservation, at the end of the unit. In addition, there is ample evidence that even students in primary school can successfully use systems and transfer ideas to make sense of phenomena (Lacy, Tobin, Wiser, & Crissman, 2014; Tobin et al., 2018, 2019). Further, a majority of students connect energy and

systems to fields in phenomena that involve interaction-at-a-distance without using forms. This contradicts the argument put forward by Constantinou & Papadouris (2012) and Millar (2005), that energy forms and transformations are needed to make sense of such phenomena. Thus, it appears as if forms may be an easy idea to begin talking about energy but not necessarily easier than emphasizing energy transfers between systems. At the same time, few students in forms-based instruction progress towards conservation while students in the systems-transfer unit make progress towards that idea. Similarly, few students in forms-based instruction develop an integrated knowledge about energy (Lee & Liu, 2010), whereas students in the systems-transfer unit developed well-organized knowledge networks. Lastly, the persistent finding that energy learning appear to go through forms may just be an example for how learning progressions research without an instructional component filters non-mainstream progressions (Duncan & Hmelo-Silver, 2009; Duncan & Rivet, 2013; Hammer & Sikorski, 2015). Taken together, it appears as if an energy learning progression based on transfers of energy between systems may present a promising alternative to forms that warrants further research. Because the generalizability of our findings is limited by sample size, especially the relatively small number of participating schools and teachers, a scale-up would be one viable route.

Beyond the broader issue of a possible transfer-only learning progression, our results also present case for emphasizing the substance ontology in energy instruction. Students successfully tracked energy in an instructional approach that corresponds with a substance ontology for energy, even in phenomena where students struggle because fields or dissipative processes are involved. This supports the argument that the substance ontology can be a productive stepping stone towards conservation (Brewer, 2011; Duit, 1987; Falk et al., 1983; Scherr et al., 2012; Swackhamer, 2005) and extends the empirical findings of Kesidou & Duit (1991). It is noteworthy, that students continue to track energy successfully in phenomena that include dissipation, as students are known to be prone to abandon conservation in dissipative phenomena (Daane, McKagan, Vokos, & Scherr, 2015; Tobin et al., 2019). This also

supports the theoretical argument for how an emphasis on energy transfers between systems supports students to acknowledge conservation in dissipative phenomena put forward in publication IV.

According to Duit (1987) one main criticism of the substance ontology is that it may promote that students develop the conception that energy really is a substance. This assertion has not been supported empirically yet (Scherr et al., 2012) and while the studies presented in this dissertation did not focus on how students conceptualize energy, we have also found no evidence to support this. This result mirrors the finding of Vosniadou & Skopeliti (2019) that drawing on existing reasoning patterns such as the substance ontology in learning about new complex ideas does not lead to an increase in students' misconceptions and supports the supposition that the transfer-only approaches consistently presents energy as belonging to the same ontological category, providing a more coherent picture of energy than forms-based approaches. Lastly, one may argue that relying on a substance ontology in introductory energy instruction only leads to ontological confusion later because at some point one will have to discuss that energy is not a substance. However, emphasizing that the substance ontology is a model of energy (Gray et al., 2019; Harrer, 2017; Scherr et al., 2012), provides valuable opportunities to integrate the scientific practice of modelling with the disciplinary core idea of energy to foster knowledge-in-use, e.g., by discussing the applicability, usefulness, and limits of the substance ontology, all important aspects of the practice of scientific modelling (NGSS Lead States, 2013).

#### **THE ROLE OF INTEGRATED KNOWLEDGE FOR KNOWLEDGE-IN-USE**

The findings in publication III emphasize the importance of building integrated knowledge for knowledge-in-use and support the premise of modern educational standards to focus on core ideas or basic concepts. Students in the systems-transfer approach built a coherent set of ideas around the central idea of energy transfer over the course of the unit and there is a strong relationship between the coherence of their knowledge networks and their

ability to apply those ideas in knowledge-in-use assessments. While these results generally support numerous previous findings that better organization of ideas leads to improved performance in applying them (Bransford, 2000; Kauertz & Fischer, 2006; Lee & Liu, 2010; O. L. Liu et al., 2015; Nordine et al., 2011; Won, Krabbe, Ley, Treagust, & Fischer, 2017), they extend them as previous research primarily relied on multiple-choice assessments.

Further, the findings in publication III provide empirical support that energy(transfer) is indeed a core idea or basic concept (National Research Council, 2012; Sekretariat der ständigen Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland, 2004) because students successfully organized their knowledge *around* energy. Lastly, the analytical approach developed in publication III allows to investigate the individual importance of constituent ideas of major multifaceted ideas like energy, e.g., the relative importance of transfer and transformation ideas in making sense of phenomena (for students in a forms-based approach).

#### **PROJECT-BASED LEARNING: HOW DRIVING QUESTIONS AND TOOLS CAN SUPPORT STUDENTS IN DEVELOPING A COHERENT SET OF IDEAS**

Publication I emphasizes how focusing on only necessary ideas and developing a need-to-know for these ideas allows to successfully introduce ideas such as fields that are considered challenging even at the university level (Furio & Guisasola, 1998; Rainson, Tranströmer, & Viennot, 1994) in middle school. Even more, students connect these ideas coherently to make sense of phenomena, i.e., they demonstrate knowledge-in-use about energy. But what establishes a need-to-know? Publication I and II suggest, that the carefully arranged series of phenomena, that are investigated using the Energy Transfer Model as a cognitive tool, set up students to establish the connections between energy, systems, and fields. This supports the premise of coherent curriculum, that if curriculum provides opportunities for students to establish connections between ideas, this supports students in developing a coherent set of ideas, i.e., integrated knowledge (Roseman, Linn, & Koppal, 2008), and contradicts the concern that designing curriculum for coherence may

undermine students opportunities to develop integrated knowledge (Sikorski & Hammer, 2017).

### **IMPLICATIONS FOR RESEARCH**

Research into learning progression often draws on cross-sectional samples and in consequence has no instruction component (e.g., Herrmann-Abell & DeBoer (2017)). The finding that students progress towards conservation without going through forms supports concerns that this practice potentially leads to filtering individual, potentially effective, instructional approaches in favor of dominant instructional approaches (Hammer & Sikorski, 2015). This concern appears especially relevant in domains where how to teach them is as heavily debated as in energy. Here, careful design-based research that tracks instruction over time to explore the potential of various progressions is probably more effective than having large samples as e.g. Herrmann-Abell & DeBoer (2017). In contrast, when there is a small set of established alternative progressions or one has detailed questions about a generally accepted progression, large samples allow to tackle these questions with the necessary precision.

Precision is also needed to further disentangle the relation between integrated knowledge and knowledge-in-use. While publication III established that both are strongly associated, the correlational nature of the results does not allow to determine how these constructs influence each other, that is, how does applying knowledge in knowledge-in-use tasks support knowledge integration? This probably reciprocal relationship (National Academies of Sciences, Engineering, and Medicine, 2018) however has important implications for how we design instruction and curriculum. In how many different contexts do students have to use the same set of ideas to establish strong connections? What are relevant features of these contexts? Do they have to apply these ideas with different practices and which practices are more effective for establishing connections?

Lastly, the results in this dissertation highlight the importance of empirical investigations for science education research. Numerous energy representations have been proposed, used, and argued for and against (Ametller & Pintó, 2002; Scherr et al., 2012; van Heuvelen & Zou, 2001) – all with little to non-existent empirical support. Elaborate theoretical arguments have been presented for and against forms of energy (Constantinou & Papadouris, 2012; Duit, 1987; Ellse, 1988; Falk et al., 1983; Kaper & Goedhart, 2002; Millar, 2005), some with very specific claims about what ideas are needed to explain phenomena more easily (Constantinou & Papadouris, 2012; Millar, 2005). Again, these arguments relied on little empirical support. The publications in this dissertation have addressed these questions empirically, advancing the fields' understanding about these issues. However, why have those questions not been addressed empirically earlier? Why did scholars feel so confident theoretical arguments? Researchers may have fallen prey to their expertise. Bias is a natural side effect of knowledge. Sometimes this bias is useful, e.g., when neutrinos seemed to move faster than light, scientists questioned the measurement, not the general relativity because it has been thoroughly tested. However, sometimes this bias undermines learning (National Academies of Sciences, Engineering, and Medicine, 2018), e.g., when strong prior beliefs lead to ignorance of new evidence (Kahan et al., 2012). Similarly, the science educators that claimed that using transformations to make sense of interactions-at-a-distance is easier than using transfer have expertise in student learning about energy and in how to use energy from a physics perspective. The bias that comes with this expertise may obscure alternatives to near canonical solutions. The findings in this dissertation underline the need for empirical research in science education and may inspire to reconsider other instructional challenges where there seems to be no feasible alternative.

#### **IMPLICATIONS FOR PRACTICE**

Constructing an Energy Transfer Model (ETM) supported students in the systems-transfer approach in applying energy ideas to make sense of phenomena, especially in recognizing that energy always has to come from or go



to somewhere, i.e., is conserved. More generally though, the basic structure of the ETM broadly aligns with the structure of other representations that emphasize transfer, e.g., energy tracking diagrams (Scherr et al., 2016). In line with findings from Tobin et al. (2018) this should encourage teachers that energy representations that emphasize transfer can support students in tracking energy without violating conservation.

Publication III presents a case for building curriculum around core ideas such as energy as students in fact developed knowledge networks around energy. The U.S. and German science standards emphasize learning around core ideas but at least in Germany, texts books (e.g., Bader, Dorn, & Drehmann, 2015) and curricula (e.g., Ministerium für Kultus, Jugend und Sport Baden-Württemberg, 2016) still rarely emphasize how basic concepts such as energy connect different contexts. Curriculum designers, teachers, and teacher educators need to become more aware of how emphasizing learning around core ideas and basic concepts supports students and research and development work should be directed towards developing learning environments that emphasize learning around core ideas and basic concepts.

Further, publication III showed having that well-organized knowledge networks is strongly associated with students' knowledge-in-use. This underlines that having a well-developed knowledge base is essential for knowledge application (Bransford, 2000). In consequence, learning about scientific practices should happen in contexts where students already possess a firm basis of the required disciplinary knowledge.

Finally, the systems-transfer unit addresses three complex ideas in middle school – energy, systems, and fields. Given the complexity of the ideas, the unit emphasizes the role of a cognitive tool in supporting students, establishing a need-to-know before introducing complex ideas, and only introduces the absolutely necessary ideas about systems, energy, and fields. Those principles are all grounded in project-based pedagogy (Krajcik & Shin, 2014) and, students' successes in learning about systems, energy, and fields reported in publications I, II, III and Fortus et al. (2019) showcase the power of

this pedagogical approach. While it can often be challenging to follow this approach, e.g., establishing a need-to-know, it is worthwhile for educators to take up this challenge.

### **FUTURE DIRECTIONS**

Nordine et al. (2019) argue that a transfer-only approach may support students not only in learning about energy in physics but also across domains as biology or geo-science frequently draw on the idea of energy transfer or “flow” through systems but rather rarely discuss forms. Alignment across disciplines should support learning about energy when students apply the *same* set of energy ideas in multiple contexts (Bransford, 2000) and at the same time support learning about these new contexts as energy ideas may help students to identify familiar structures that support knowledge integration (Bransford, 2000; Chi et al., 1981; National Academies of Sciences, Engineering, and Medicine, 2018). Thus, one direction for future research is to investigate the potentials of emphasizing the transfer-only perspective across the sciences. To investigate to what extent this supports learning about energy across domains, one may either draw on longitudinal designs on longer time scales as e.g., in Fortus et al. (2015), or on a smaller time scale, investigate future learning in respectively designed assessments (Bransford & Schwartz, 1999).

Lastly, to test whether an energy learning progression around the idea of energy transfers between systems is feasible, future research will have to investigate how students can successfully progress beyond middle school, i.e., from the qualitative model in the systems-transfer approach to a quantitative model of energy. Similarly, it will be important to investigate how students from a systems-transfer approach fare when they are confronted with forms in future instruction, be it in the remainder of K-12, university, or informal learning opportunities.

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## **EIDESSTATTLICHE ERKLÄRUNG**

Hiermit erkläre ich, dass die vorliegende Dissertation – abgesehen von der Beratung durch meinen Betreuer – nach Inhalt und Form meine eigene ist. Sie wurde weder im Ganzen noch in Teilen an einer anderen Stelle im Rahmen eines Promotionsverfahrens vorgelegt. Teile dieser Arbeit wurden bereits in Form von Zeitschriftenartikeln publiziert bzw. sind zur Publikation eingereicht. Die Arbeit ist unter Einhaltung der Regeln guter wissenschaftlicher Praxis der Deutschen Forschungsgemeinschaft entstanden. Es wurde mir kein akademischer Grad entzogen.

Kiel, den 01.08.2019

Marcus Kubsch