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Hunter G. Close[a] & Rachel E. Scherr[b]
[a] Department of Physics, Texas State University, San Marcos, TX, USA
[b] Department of Physics, Seattle Pacific University, Seattle, WA, USA

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Enacting Conceptual Metaphor through Blending: Learning activities embodying the substance metaphor for energy

Hunter G. Close[a*] and Rachel E. Scherr[b]
[a]*Department of Physics, Texas State University, San Marcos, TX, USA;* [b]*Department of Physics, Seattle Pacific University, Seattle, WA, USA*

We demonstrate that a particular blended learning space is especially productive in developing understanding of energy transfers and transformations. In this blended space, naturally occurring learner interactions like body movement, gesture, and metaphorical speech are blended with a conceptual metaphor of energy as a substance in a class of activities called Energy Theater. We illustrate several mechanisms by which the blended aspect of the learning environment promotes productive intellectual engagement with key conceptual issues in the learning of energy, including distinguishing among energy processes, disambiguating matter and energy, identifying energy transfer, and representing energy as a conserved quantity. Conceptual advancement appears to be promoted especially by the symbolic material and social structure of the Energy Theater environment, in which energy is represented by participants and objects are represented by areas demarcated by loops of rope, and by Energy Theater's embodied action, including body locomotion, gesture, and coordination of speech with symbolic spaces in the Energy Theater arena. Our conclusions are (1) that specific conceptual metaphors can be leveraged to benefit science instruction via the blending of an abstract space of ideas with multiple modes of concrete human action, and (2) that participants' structured improvisation plays an important role in leveraging the blend for their intellectual development.

Keywords: *Embodied cognition; Conceptual metaphor; Conceptual blending; Energy Theater*

*Corresponding author. Department of Physics, Texas State University, San Marcos, 78666 TX, USA. Email: hgclose@txstate.edu

Introduction

The general cognitive phenomenon of conceptual metaphor, recognized as significant in recent developments in cognitive science (Fauconnier & Turner, 2002; Lakoff & Johnson, 1999; Lakoff & Nuñez, 2000; Sfard, 1994), is also relevant to science education. We demonstrate that a conceptual metaphor of energy as a substance (Amin, 2009; diSessa, 1993; Duit, 1987; Falk, Hermann, & Bruno Schmid, 1983; Millar, 2005; Scherr, Close, Close, & Vokos, 2012; Scherr, Close, McKagan, & Vokos, 2012; Swackhamer, 2005) is particularly productive in developing understanding of energy transfers and transformations. We provide evidence that an embodied learning activity called Energy Theater engages learners with key conceptual issues in the learning of energy. In Energy Theater, each participant identifies as a unit of energy. Groups of learners work together to represent the energy transfers and transformations in a specific physical scenario. Objects in the scenario correspond to regions on the floor. As energy moves and changes form in the scenario, participants move to different locations on the floor and change their represented form. In previous work (Scherr et al., 2013), we have observed that Energy Theater supports the participants in engaging with key conceptual issues of energy, namely, disambiguating matter and energy, and theorizing mechanisms for energy processes; and that this engagement is supported by the material structure of the Energy Theater environment and the embodied action that it promotes. This environment was designed to be a metaphorical learning space with both a set of strict rules of engagement and with plenty of room for improvisation and emergent events and meaning. Energy Theater's metaphorical aspect is reminiscent of children's (or adult actors') imaginative play, in which a group agrees to pretend that things, people, and settings are not what they are in a literal sense. Energy Theater's rule structure is like that of a board game or team sport, in which rules are laid out, but the outcome is not determined by the application of these rules; instead it is achieved through an interplay between an adherence to the rules and many free, unplanned choices on the part of the participants. As we reflected on this combination of the three elements of metaphor, rules of engagement, and improvisation inherent to Energy Theater, it became apparent to us that a particular theory of cognition, *conceptual blending*, was very appropriate as a theoretical apparatus for understanding the workings of Energy Theater, especially in terms of the intellectual development of the participants. Thus, our present research question is: 'How can the perspective of conceptual blending account for the success of Energy Theater in connecting participants with key conceptual issues of energy?' To answer this question, we analyze new episodes of participant interactions, we add further evidence of participants' engagement with key conceptual issues, and we explore the use of concepts from *conceptual blending*, which we explain in further detail below in the section 'Vital Relations among Elements in Energy Theater'.

We justify the application of conceptual blending theory to our data in three ways: First, though Energy Theater was first designed without an explicit awareness of conceptual blending, its structure has always been formulated as a correspondence of elements in the concrete learning environment (e.g. people, ropes, hand signs) to

elements in a separate 'physical scenario' space, with a spirit of the fusion of identity (e.g. 'I *am* a unit of energy', 'this bounded area on the floor *is* the pulley'), and with rules for human action (e.g. exactly one hand sign at a time) that are meant to communicate rules of the dynamics of energy (a unit of energy has exactly one form at a time). Second, the single overarching goal of all conceptual blending, according to Faucconier and Turner (2002, p. 322) is to 'achieve human scale'. We believe the achievement of human scale is a fundamental characteristic of Energy Theater. Thus the study of Energy Theater is in a reliable manner a study of conceptual blending itself. Third, by bringing the theory of conceptual blending to the analysis of our video records of Energy Theater, we illustrate its natural fit for understanding the meaning of events for participants.

As we analyze video episodes in detail, we take the theoretical perspective that the universal properties of an event or phenomenon emerge from the specifics of a particular case, rather than from the patterns that emerge across cases (Erickson, 1986). Our methodology is to identify video episodes in which learners engage with energy concepts in general and conduct detailed analysis to characterize the specific concepts with which they engage (Jordan & Henderson, 1995). A participationist theory of learning, in which learning is indicated by changes in speech and behavior, supports ethnographic analysis of learners' embodied interactions with each other (Lave, 1991; Sfard, 1998; Vygotsky, 1986; Wertsch, 2007) and the material setting (Hutchins, 1995; Jordan & Henderson, 1995; Nemirovsky, Rasmussen, Sweeney, & Wawro, 2011; Stevens, 2000). We conduct detailed analysis using conceptual blending theory to build plausible causal links between specific features of Energy Theater and the conceptual engagement that we observe (Maxwell, 2004a, 2004b; Salmon, 1998). The novel contribution of this work is to account for energy learning in terms of conceptual blending theory.

Design of an Embodied Learning Activity Based on the Substance Metaphor for Energy[1]

Embodied Cognition Perspective

In an embodied cognition perspective, all abstractions are understood in terms of basic sensory-motor experiences such as object permanence and movement (Lakoff & Johnson, 1999; Lakoff & Nuñez, 2000). Ideas such as time are expressed with embodied metaphors: for example, we might say that we are 'halfway through' the year, as though a year had spatial extent and we were moving relative to it. Human use of embodied metaphors is natural, unconscious, and pervades our talk; we often express conceptualizations of events, activities, emotions, ideas, and so on as being entities or substances. Embodied metaphors are often especially evident in the verbs and prepositional phrases used together with the terms of interest. For example, to say someone is 'in trouble' or 'close to graduation' conceptualizes these states as being locations, and to say that someone 'got an idea' or 'has a headache' poses these attributes as being possessions (Lakoff & Johnson, 1999). Grammatical

indicators such as these can identify learner ontologies for energy—the kinds of things that people think of energy as being. Gestures and other bodily actions can also indicate ontologies (Close & Scherr, 2012; Scherr et al., 2013). Influential research in cognitive science has demonstrated that ontological categorization is key to understanding physics concepts (Chi, 2005; Chi & Slotta, 1993; Slotta & Chi, 2006).

The Substance Metaphor for Energy

Certain statements pose energy as being a substance-like quantity—a kind of 'stuff'—and objects as being containers that can have such stuff in them:

> The gas *has* energy.
>
> Where did the energy *in* the gas *come from?*

Statements that implicitly treat energy as a substance are ubiquitous in physics textbooks and the words of famous physicists. Even statements that carefully avoid any explicit characterization of energy as anything other than an abstract numerical quantity use an implicit substance metaphor:

> We now introduce a third type of energy that a system can *possess* (Serway & Jewett, 2007).
>
> Thus, the flying duck *has* a kinetic energy of 6.0 J (Halliday, Resnick, & Walker, 2008).
>
> ... When we *put* energy *into* the gas its molecules move faster and so the gas gets heavier (Feynman, Leighton, & Sands, 1969).[2]

This imagined substance is not a material fluid; rather it is a 'quasi-material' substance, one that includes certain properties of material substances (e.g. localization and conservation) but not others (e.g. mass, volume, viscosity). The substance metaphor for energy has limitations (Amin, 2009; Duit, 1987): it suggests that energy is not purely a mathematical quantity (Arons, 1965; Feynman et al., 1969; Warren, 1982, 1986), it does not support a concept of negative energy (Dreyfus et al., 2014), it does not include energy degradation or dissipation (Daane, McKagan, Vokos, & Scherr, 2015; Daane, Vokos, & Scherr, 2014), and it does not admit energy's frame-dependence or its delocalization in quantum mechanics, among other limitations (Duit, 1987). We have selected a substance metaphor for energy as a primary focus of our instruction because of its advantages for teaching conservation, transfer, and flow (Brewe, 2011; diSessa, 1993; Duit, 1987; Falk et al., 1983; Millar, 2005; Scherr, Close, McKagan, et al., 2012; Swackhamer, 2005). A substance metaphor supports the following features:

> *Energy is conserved.* This key feature is a primary advantage of the metaphor.
>
> *Energy is localized*, i.e. it is associated with a spatial location, even if spread out.
>
> *Energy is located in objects,* which are metaphorically represented as containers for energy.
>
> *Energy can change form.* As a material substance can change form (e.g. when a ball of clay is remolded, or when water freezes or boils), energy also can be understood to change in appearance or presentation while remaining fundamentally the same. Forms, in our

model, are categories of evidence that energy is present or changing, and thus an important means of connecting a unified energy concept to a variety of observable phenomena (McKagan, Scherr, Close, & Close, 2012).

Energy is transferred among objects and *energy can accumulate in objects.* Flow corresponding to a conserved quantity (i.e. a quantity subject to the continuity equation) is a key concept in physics, appearing here as energy transfer (and elsewhere as mass transfer, charge transfer, and momentum transfer, in both classical and quantum mechanical contexts).

These features constitute a powerful conceptual model of energy that may be used to explain and predict energy phenomena.

Energy Theater

Energy Theater is a learning activity designed to embody the substance metaphor for energy (Scherr, Close, Close, et al., 2012). In Energy Theater, each participant identifies as a unit of energy that has one and only one form at any given time. Groups of learners work together to represent the energy transfers and transformations in a specific physical scenario (e.g. a refrigerator cooling food or a light bulb burning steadily). Participants choose which forms of energy and which objects in the scenario will be represented. Objects in the scenario correspond to regions on the floor, indicated by loops of rope. As energy moves and changes form in the scenario, participants move to different locations on the floor and change their represented form. The rules of Energy Theater, which are presented explicitly to participants, are:

Each person is a unit of energy in the scenario.

Regions on the floor correspond to objects in the scenario.

Each person has one form of energy at a time.

Each person indicates his or her form of energy in some way, often with a hand sign or iconic movement.

People move from one region to another as energy is transferred, and change hand sign as energy changes form.

The number of people in a region or making a particular hand sign corresponds to the quantity of energy in a certain object or of a particular form, respectively.

Examples of forbidden actions would be:

A person identifies as an object rather than a unit of energy.

A person identifies as the energy of a particular object (rather than as a unit of energy that happens to be in the object at a particular moment in time).

A region on the floor is designated a form of energy (such as kinetic energy), rather than an object.

A person is energy for only part of the activity and then sits down or otherwise leaves the scenario.

> A person remains energy but moves to an unmarked region on the floor, corresponding to nowhere in particular.
>
> The verbal narrative of the physical processes in the scenario is inconsistent with the embodied 'narrative' in the Energy Theater space, e.g. a box is said to move at constant speed but the number of units of kinetic energy in the region corresponding to the box does not remain constant.

Examples of extemporaneous moves that are beyond the scope of the rules and can contribute to emergent meaning would be:

> A person moves when others think that person should stay, causing an interruption in action and a discussion of a conceptual issue.
>
> A hand sign corresponding to a form of energy causes confusion due to its visual similarity to another sign.
>
> By chance, a group has an odd number of people and therefore cannot divide the total energy into two equal parts, causing people to attempt to account for an energy unit that is 'left over.'
>
> People imagine and recount amusing consequences for the physical system if a mistaken enactment of Energy Theater were in fact correct, or if energy that is neglected in the enactment, but which is understood to be present in the scenario, were in fact absent. For example, people might joke that an object with no represented thermal energy is at a temperature of absolute zero, or a man pushing a box dies when his energy is exhausted in the enactment.

In designing Energy Theater, we have sought to specifically harness the affordances of the energy-as-a-substance metaphor by developing a representation that embodies that metaphor. Since one of the most basic experiences of substances is that of object permanence, we developed a representation in which energy is explicitly shown as being an object or objects; and since a particularly cognitively compelling sense of permanence might be attached to the self, and use of the human body might have special significance for learning, we developed a representation in which people identify as units of energy. Energy Theater is thus embodied in two separate senses: it makes explicit use of a particular experientially grounded metaphor (energy as a quasi-material substance), and it uses the human body to symbolize physical entities (Stevens, 2012). A variety of other embodied learning activities have been developed in which the body represents mathematical entities (Touval & Westreich, 2003), molecules (Ross, Tronson, & Ritchie, 2008), electrical charges (Manogue et al., 2001; Singh, 2010), celestial bodies (Morrow, 2000; Reinfeld & Hartman, 2008; Richards, 2010), computer science entities (Begel, Garcia, & Wolfman, 2004), components of a dynamic system (Colella, 2000; Resnick & Wilensky, 1998), cellular processes (Chinnicci, Yue, & Torres, 2004; Wyn & Stegnik, 2000), and even literary devices (Zimmerman, 2002).

Conceptual Blending Theoretical Perspective on Embodied Learning Activity

We understand Energy Theater as a blend of two spaces, in the manner described by the theory of cognitive or conceptual blending (Fauconnier & Turner, 2002; hereafter,

'F&T'). According to conceptual blending theory, blends are ubiquitous, sometimes spectacular but most often unnoticed, and very useful for human thinking and communication. (Energy Theater is probably not one of those everyday, usually unnoticed blends.) A blend always involves at least two input spaces and creates a blended space that incorporates some elements and relations from the input spaces. For example, 'Weird Al' Yankovic has made a successful career as a satirical musical artist by taking (in many, but not all, cases) just the music of a popular song (e.g. 'Happy', by Pharrell Williams), creating new lyrics with a center of meaning in another domain (self-serving, tasteless behavior) and combining them to make a new song ('Tacky'). In the case of Energy Theater, the two input spaces are (1) the literal learning space with people, a floor, ropes for bounding regions on the floor, and other incidental environmental features (such as furniture), and (2) the space of the physical scenario (e.g. a box sliding down an incline while slowing down), which may be demonstrated physically or is sometimes only imagined. The physical scenario space may also be modeled as a blend of two spaces: the concrete, observable space of objects, and the abstract, imaginary space of energy. We do not pursue an analysis of this object-energy blend in this article, though we recognize that for most participants this blended 'physical scenario' space is surely hazy and incomplete. One major purpose of the Energy Theater blend is to clarify the internal relational structure of the physical scenario space; that is, a major purpose is to teach physics.

Vital Relations among Elements in Energy Theater

Vital relations in conceptual blending are those fundamental relationships between any elements in any of the spaces (F&T, p. 93). Vital relations between elements A and B could be of various forms: A causes B, A represents B, A is a part of B, A happens before B, A is above and slightly to the left of B, A looks like B, A is B, etc. If the relationship is between elements within one space, it is called an inner-space vital relation; if it is between elements in two different spaces, it is called an outer-space vital relation. For instance, we understand a photograph of a person to be a representation of that person; the vital relation is representation. Representation can compress in a blend to an inner-space vital relation of uniqueness, in which we treat the photograph and the person as one and the same, perhaps saying, 'Look at the expression on your face!' An exhaustive set of vital relations and some descriptions of their dynamics are given in F&T, especially chapters 6 and 16.

Using the language of *vital relations*, we understand the 'people' input space to have the following structure that is imported to the blended Energy Theater space: People are *elements* in the space and are interchangeable members of the *category* 'participant'. The space also contains 'region' elements that are marked by closed loops of rope; these bear a special *spatial* inner-space vital relation of containment to the people: each person is either inside or outside any given rope. Each person makes a single hand sign at a time, and this hand sign is understood as a changeable *property* of the person. Actions in the people space also gain meaning by their *time* ordering—whether event A occurs before, after, or at the same time as event B is often important

for people in general, and it is also important in Energy Theater. Despite being members of a category, and being able to function as interchangeable, each person also is easily distinguishable, if their distinguishability can provide some cognitive advantage. Indeed, each person has a flexible self-*identity* relation that can be engaged or disengaged; a person can shift identity from one interaction sequence to another to disconnect actions and prevent them from gaining meaning from each other by sharing a context, or a person can maintain an identity (especially when acting as a single energy unit) to express *change* through different sequential actions. This resource for human interaction is easily seen in the act of telling a story: we understand when the storyteller recalls a conversation between Harry and Sally that some utterances belong to Harry and some to Sally, and that some other utterances by the storyteller belong entirely outside the conversation between Harry and Sally. We present examples of the dynamics of identity in Energy Theater below in the section 'Energy Learning through Embodiment of the Substance Metaphor'.

Inherited Structure from Input Spaces

Part of the utility of blends is that the input spaces can provide structure to the blend. In the example of Yankovic's satiric songs, the blended song inherits its musical structure from the parodied song. In Energy Theater, the 'people' space brings conceptual structure to the blend partly through its material structure (Hutchins, 1995, 2005), including the facts that people are conserved, each person has a location, and, when counting people, the whole is automatically the sum of the parts. When the people become units of energy, these structures are inherited from the 'people' input space into the blended space, so that units of energy are conserved, located, and easily summed.

The 'people' input space provides structure to the activity also through the structure of existing social resources (Goodwin, 2000; Greeno, 1998; Hutchins, 1995). Part of the structure is provided by the explicit rules of Energy Theater, which perhaps seem arbitrary at first. However, this arbitrariness can still be experienced as culturally coherent in that many games and puzzles are presented initially as a set of arbitrary rules whose value or meaning is discovered through their application. Other aspects of social structure for Energy Theater provided by the people input space come from participants' experience managing disagreement within groups of people. The social structure includes both the explicit rules of Energy Theater and other tacit rules of a broader culture, like the tendency to work out disagreements through debate and compromise. Thus, in the blended space, units of energy move around and transform and also debate with each other about how to move around and transform.

The scenario input space brings less structure, or a less reliable structure, to the blend, since it is sensitive to the specific physical scenario and to the media by which the scenario is apprehended (e.g. experiment, common memory, quasi-theoretical simulation, or intuitive prediction), and to what the participants know or believe about the scenario. For example, participants may think the cart speeds up, or the ice

water maintains a constant temperature as it melts, or may have other partial information and understanding that can help to guide and constrain the participants' solution to the puzzle of how to depict the energy. Hence many details of the emergent structure of the Energy Theater blend are unpredictable. The strict rules for symbolic engagement in the blended space are intended in the design of the activity to result through their repeated application in a clear, shared understanding of various scenario input spaces.

Regardless of the changing conditions of the physical scenario input space, some particular 'outer-space' vital relations are likely to hold: First, almost inevitably the relation of perceptible *similarity* between participants in the people space and the objects in the scenario space will lead participants to form an erroneous *uniqueness* relation between themselves and some object (i.e. someone becomes an object instead of energy). Conversely, initially the energy in the scenario space is likely 'perceived' (or not perceived at all) as *dissimilar* to participants in the people space. *Analogy* and *disanalogy* are outer-space vital relations that F&T claim usually compress into *similarity* and *dissimilarity* in a blend; that is, those things that are understood to be abstractly alike (or not alike) are reconceived to appear alike (or not alike). Therefore, it seems reasonable that in Energy Theater, participants must effortfully remember that what appears alike in the blend does so despite the fact that it is not meant to be analogous in the relation between elements in the input spaces. Second, in a move that is neither prescribed nor forbidden by the rules of Energy Theater, participants regularly compress *part-whole* relations into *uniqueness*; participants often show through their own actions what they believe many, or an indeterminate number of, energy units would do. The part-whole relation is shown to be compressed in the blend through the typical *lack* of discussion about how exactly to scale up the action from one person to seven people to a thousand energy units.

Another crucial component of the conceptual structure of the blended space is the fact that an Energy Theater enactment is by nature a group product. Each person in the group has direct authority over the behavior of one unit of energy, the individual self; but the product of the group's work is one coherent Energy Theater enactment, regardless of the number of opinions in the group about what should happen to the many energy units. As when a barbershop quartet sings a chord, one participant who makes a distinctive contribution changes the whole result for everyone. To whatever degree each person is invested in a particular proposed global solution to an Energy Theater problem, that person is invested to the same degree in persuading others to see the value in the proposed solution, since any global proposal requires others' willful cooperation if it is to be part of the final performance or solution. The result is a high intensity of negotiation of meaning (Scherr et al., 2013).

Summary

In summary, Energy Theater cognitively blends learners and energy together to create an embodied problem-solving and concept-exploring space. The purpose of the specific blend is to create a situation that stimulates intense negotiation of meaning

about energy. The negotiation of meaning arises mostly naturally, in the sense that the interaction of human need for meaningful experience with the structure of the activity is sufficient to call for the negotiation; little direct instructor intervention is required after participants have understood the basic structure for activity. The fact that this negotiation of meaning is officially approved as on-task behavior promotes genuine participation and gradual transformation of the learners. The specific character of the negotiation is authentic to the broader community of practicing physicists in the sense of using disciplined imagination of the dynamics of hypothetical entities (Ochs, Gonzales, & Jacoby, 1996).

Research Methodology

Methodological Perspective

The use of rich records of naturally occurring activities as evidence of learner knowing promotes and supports a socio-cultural view, in which learning is a process that shows in what participants do and say together (Sfard, 1998, 2007). For this view of learning, ethnographic perspectives are naturally relevant (Erickson, 2004; Mcdermott, Gospodinoff, & Aron, 1978; Schegloff, 1997). We identify with the interpretive tradition (Erickson, 1986), in which the phenomena of interest for learning are the meaning of activities for the participants. This perspective asserts that participants create meaningful interpretations of physical and behavioral occurrences; that they take action based on their interpretations, that is, interpretations are causal; and that these interpretations are often invisible to participants, who treat their interpretations as reality (Denzin & Lincoln, 2005). A primary function of the ethnographic researcher in this tradition is to 'make the invisible visible' (Goodwin, 1994): to describe the implicit social and cultural organization that shapes the participants' activity (Anderson-Levitt, 2006).

Participants

Our data consists of videotaped episodes of teachers in a professional development course analyzing the energy dynamics of specific real-life physical scenarios. The episodes are from video records of professional development courses for K-12 teachers offered through Seattle Pacific University as part of the Energy Project, a six-year, NSF-funded project to develop and study teacher practices of formative assessment in the context of energy teaching and learning. Teachers participate primarily in order to gain content understanding of energy for themselves, and secondarily to translate that content understanding into classroom activities that are aligned with national science learning standards (National Research Council, 2012; NGSS Lead States, 2013) and other constraints. Participating teachers teach in a wide range of situations, with an enormous variety of populations, material resources, institutional constraints, and expectations for science learning. For this reason, the professional development experience does not provide teachers with a curriculum or script to

enact in their own classrooms. Instead, project team members work to encourage and support each teacher in creatively applying sound conceptual understanding to their own circumstances. Some teachers elect to use Energy Theater in their own classrooms (Daane, Wells, & Scherr, 2014).

Data Collection

Energy-centered professional development courses offered by the Energy Project are documented with video, field notes, and artifact collection (including photographs of whiteboards, written assessments, and teacher reflections). In each course, teachers are grouped into 4–8 small groups, and two groups are recorded daily. As researcher-videographers document a particular course, they take real-time field notes in a cloud-based collaborative document, flagging moments of particular interest and noting questions that arise for them in the moment. Later, the researcher-videographers or other members of the Energy Project identify video episodes to share with a research team. We use the term 'episode' to refer to a video-recorded stretch of interaction that coheres in some manner that is meaningful to the participants (Jordan & Henderson, 1995). These episodes are the basis for collaborative analysis, development of research themes, literature searches, and the generation of small or large research projects.

Episode Selection

The episodes in this paper were selected from an Energy Theater enactment initially observed by author R.E.S. in the summer of 2013. In this enactment, participants negotiate and perform Energy Theater for adiabatic compression of a gas. R.E.S. highlighted this particular Energy Theater enactment on the basis of audio-visual clarity, sustained learner engagement with a physical scenario, and appropriate implementation of Energy Theater, that is, the participants mostly followed the rules specified in section 'Energy Theater'. The enactment analyzed in this paper is not the only enactment with these features, and we do not present evidence that it is a representative enactment—that is, we do not present evidence that most other enactments have the same features (though our experience suggests that many of them do). Rather, we put forward this enactment as a *case* of Energy Theater: an instantiation through which we may identify universal features of Energy Theater that are evident in the concrete details of its practice. We expected that this enactment would help us to identify some of the ways in which conceptual blending is manifested in the activity.

Analysis

After identifying this enactment as one likely to contribute to answering our research question, each author watched the video multiple times, creating a detailed narrative of events as well as a sketch transcript focusing primarily on speech. On the basis of the

narrative, sketch transcript, and multiple viewings, two episodes were selected in which learners engage with energy concepts and with one another as they construct an understanding of energy. These episodes were isolated and transcribed in greater detail, including transcription of embodied actions. Claims were developed that responded to the research question: 'How can the perspective of conceptual blending account for the success of Energy Theater in connecting participants with key conceptual issues of energy?' We respond to this question with interpretive video analysis combined with theoretical study of conceptual blending as evidenced in human interaction. We conduct detailed analysis to describe specific features of Energy Theater and the learning events that we observe in the language of conceptual blending. In line with our participationist perspective, learning events include those in which learners' talk moves toward expert use of disciplinary language.

Energy Learning through Embodiment of the Substance Metaphor

In the episodes below, we show how Energy Theater supports a group of teachers in learning about energy. Specifically, we show how teachers' embodied engagement in the blended Energy Theater space supports them in grappling with key conceptual issues in energy. The physical scenario being considered in the episodes below involves the adiabatic compression of an ideal gas. The scenario was communicated to the teachers by the instructor of the professional development course (author R.E.S.) primarily through a projected display of a PhET simulation (Weiman, Adams, & Perkins, 2008) on the classroom screen rather than through a verbal description. In the simulation 'Gas Properties', a man (whom the teachers sometimes called 'the man' or 'Scuba Steve') pushes with his whole body on a movable wall of a container of gas, decreasing the volume of the container (see Figure 1).

The gas is depicted only in terms of its constituent particles (which the teachers sometimes called 'purple balls' because of their appearance in the simulation). In steady state, the balls move around inside the container, colliding very often with each other and the container wall. As the man moves the wall, the balls are seen to move faster. A simulated red alcohol thermometer is attached to the container and shows a rise in the level of the alcohol and an increase in the numerical temperature reading. Teachers were simply challenged to produce an Energy Theater 'solution' to the scenario, which is a routine to which they had become accustomed, having had a full two-week intensive course ('Energy I') the previous summer (2012) and one full week of instruction using Energy Theater so far in Summer 2013 in a second-year course ('Energy II'). The scenario was their seventh Energy Theater challenge so far that week. In the episodes below, seven teachers (pseudonyms Dan, Andy, Scott, Elaine, June, Denise, and Sally) begin to negotiate such a solution. Before the episodes described below begin, these teachers had already laid out three rope loops in a linear sequence of adjacent loops, each in a generic rounded rectangular shape. In the analysis below, we refer to ropes 1, 2, and 3, while the teachers refer them in blended fashion with the labels 'man', 'wall', and 'balls'.

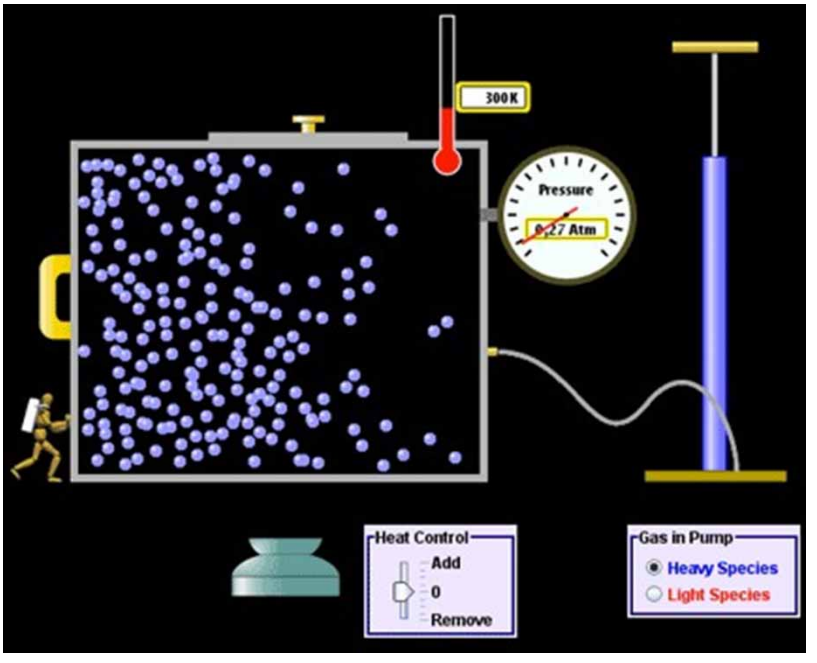

Figure 1. Screenshot from 'Gas Properties', a PhET interactive simulation

When 'doing Energy Theater' as an instructional activity, groups of participants tend to spend most of their time arguing over different proposals for enactments of Energy Theater rather than perfecting their execution of a sequence of coordinated actions. Indeed, teachers seem to take up Energy Theater primarily as a puzzle-solving tool in an intense group negotiation that hybridizes spoken discussion and argumentation with symbolic embodied action. During the planning, the effect of using the rule structure of Energy Theater is to constrain and regiment the group's thinking and argumentation with a particular theoretical perspective on energy itself.

Distinguishing among Energy Processes

In the following episode, teachers distinguish distinct energy processes (transfers and transformations) that are potentially important to the energy dynamics of the scenario (see Figure 2).

Participants make this progress by engaging with the symbolic material structure of Energy Theater in a variety of basic manners: simulating energy transfer with body locomotion, using the space as a reference frame for gesture, coordinating movement with speech, and enforcing rules of interpretation. In all of these ways, the inherited structure of the blend shapes and promotes learners' understanding.

Dan initiates the group discussion by proposing a particular Energy Theater solution in words and by 'walking it through'. After his proposal, the group considers

Figure 2. Participants negotiate Energy Theater for adiabatic compression of a gas. In this episode, participants distinguish distinct energy processes that are potentially important to the energy dynamics of the scenario

the possibility of an energy transformation that was not an explicit part of Dan's proposal. The episode is about 1.5 min long (see Supplemental data).

At the beginning of this episode, most participants are standing around the perimeter of the set of ropes. Only two participants are standing inside the ropes: Dan is inside rope 1, and Andy is inside rope 3. The transcript that follows annotates participants' speech with a description of the embodied action that accompanies it. The '==' symbol indicates an unbroken turn at talk, overlapped by another speaker (Table 1).

The intellectual progress of this episode is for participants to distinguish among related, but distinct, energy processes that comprise the energy dynamics of adiabatic compression. In particular, the participants distinguish a transfer of energy from man to wall to gas ('one pathway is kinetic energy man, kinetic energy wall, kinetic energy balls') from a transformation of energy within the gas ('the moving purple ball inside the gas is transforming into heat'). This distinction is only partially articulated at this time; for example, June refers to the gas particles transforming (rather than the energy of the gas particles), and her use of the term 'heat' is not canonical (Kraus & Vokos, 2011; Scherr et al., 2013; Scherr & Robertson, 2014). Nonetheless, the distinction between energy transfer to the gas and energy transformation within the gas is crucial to the analysis of the scenario.

When Dan initially proposes the rudiments of his Energy Theater solution, he steps through the regions and coordinates his talk (e.g. 'kinetic energy, wall') with his arrival in the corresponding region and points downward at each region, enacting the Energy Theater blend by establishing the meaning of a representative unit of energy passing

Table 1. The transcript in Table 1 annotates participants' speech with a description of the embodied action that accompanies it

Speaker	Speech	Embodied action
Dan	So one pathway is kinetic energy man kinetic energy wall kinetic energy [1 sec] balls	Stands in rope 1, points down to rope 1. Walks through rope 2, points down to rope 2. Arrives at rope 3 and points down to rope 3
Andy	Mmm-hmm	
Scott	Yeah. I think there's one other kind a tricky thing is because the size of the box changes, we are compressing the air so the air is now running into itself much more often. So it's a little more complicated than just adding some kinetic energy—we're not thumping ==	'Squeeze' gesture: Positions hands as though he is holding a package of air and moves them together Dan walks backwards to return to loop 1. Finger-flicking gesture directed at screen
Elaine	Well ==	
Scott	== a few of the molecules	
Elaine	== kinetic turns to thermal	
Scott	Well yeah, definitely!	
Andy		Steps backwards and exits rope 3
June	Can this be a separate tr—a separate transformation . . . so if she—the—not focusing on that pathway but the purple ball, the moving purple ball inside the gas is transforming into heat I guess it would have to be a kinetic-kinetic then thermal Like, can that transformation happen only here Can that pathway exist only inside. The. Molecules. [5 sec] 'Cause we've always had like a starting I feel like something's happening THAT pathway There's also something happening with the moving balls inside here.	Approaches rope 3 Turns back to her right and points to Dan in rope 1. Hand thrusts forward, toward rope 3 Steps back Steps forward into rope 3 Points down to rope 3 Pause, steps back and out Holds left palm out to Dan's position in rope 1, whistles, flips left palm around and sweeps to her left, toward rope 3 Points to rope 3 Sweeps pointer from rope 1 to rope 3 Steps back into rope 3
Dan	There's something internal	Steps forward into rope 2
June	[inaudible]	
Scott	We have some heat energy that we're starting off with ==	
Dan	So	Steps into rope 3
Scott	== they're definitely moving, we're above Absolute zero	

(*Continued*)

Table 1. Continued

Speaker	Speech	Embodied action
Dan	But what if we were moving about and we ==	Performs repeated double high-fives with Andy
June	YES	
Dan	== did this for pressure	
Andy	But	Closes fingers of high-five hands
Denise	Nooo	

from one object to the next in sequence. It might seem that his string of speech has a definite meaning on its own and that his body movement is superfluous; he describes a 'pathway' and states the form of energy and the location in each phrase. However, in a different context his words might have been interpreted as describing the presence of kinetic energy in each object (man, wall, and balls) simultaneously, rather than sequentially as a transfer. Thus, his deliberate walkthrough helps to establish the structure of the blend.

Dan's actions and words communicate vital relations that are internal to the blended space: *space*, *time*, *identity*, and *property* (form of energy). In fact, they seem even to communicate nothing besides these vital relations. The grammatical and prosodic structure of Dan's speech is shaped in part by the metaphorical space of Energy Theater and the 'questions' it 'asks' its users (Scherr, Close, McKagan, et al., 2012): Where will you stand? Where will others be at the same time? Where will you go next? What form will you be? and so on. As the space asks these questions, Dan's speech is structured to provide those answers. This idea that learner activity is substantially shaped by the forms of representation has been both argued generally and shown empirically in the case of learning of physics when algebraic structures for thinking and communicating are replaced with computer code (Sherin, 2001). Dan's concise solution description suggests that he thinks that his solution is correct in its basic form; he ends the sequence on the word 'balls' with a drop in pitch that signals the end, after which he pauses briefly and solicits agreement. Dan's solution is presented as though no other significant components will be necessary as it is adapted to a full-fledged solution involving several actors (though perhaps the timing might need to be fine-tuned). Thus, a single energy unit (Dan) becomes all the energy in the scenario for a short period, such that Dan is all the energy. Using the parlance of blending: The part-whole vital relation between the single energy unit and all the energy in the scenario temporarily compresses in the blend to uniqueness (F&T, p. 113); as a result of the compression, the single unit of energy *is* all the energy. June's concern is primarily with understanding if and how there is an energy transformation happening inside rope 3, or 'inside the molecules', perhaps to help explain how kinetic energy becomes thermal energy. June, like Dan, points to elements of the Energy Theater space and refers to them as though they were the objects they represent (man, molecules, etc.), which indicates that the intended

blend between the 'people' space and the 'scenario' space has been successful. Additionally, June's speech contains several missing pieces that are filled in through her embodied reference to the blended Energy Theater space, which incidentally placed her literally at the center of the group's interaction. Therefore it is plausible that June's meaningful contributions to the discussion are enabled through her engagement in the blend, and that without support from the blend (as it appears in the material structure of the environment), her point might have been overlooked by the group. June's engagement with the Energy Theater space in this episode is not as plainly ordered as Dan's: she steps in and out of the ropes; she interrupts her own speech to refer back to Dan's proposal and to rearticulate her concerns; she uses a mixture of gestures and locomotion to organize and express her thinking. However, June's actions assemble into a meaningful whole that is assisted by the spatial structure of the ropes, their metaphoric correspondence with objects, and by the vapor trail of Dan's proposal in her memory.

In contrast to the manners of participation of Dan and June, Scott speaks and gestures clearly and authoritatively, but in ways that are mostly not coordinated with the Energy Theater space. His body remains in one location outside and next to rope 3, and his metaphoric gestures (squeezing the gas, flicking the molecules) do not refer to the rope- objects, people-energy units, or to anyone else's motion. His ideas are potentially relevant to the group's discussion; the collisions between gas molecules can be understood as an energy transfer mechanism between molecules, and perhaps even as an energy transformation mechanism, as the means by which ordered kinetic energy becomes disordered and thereby reclassified as thermal energy. However, the response of the group to Scott's ideas is tenuous, perhaps because they find the meaning unclear as the ideas are not expressed in terms of the group's common metaphor.

Disambiguating Matter and Energy

The episode above not only shows teachers distinguishing among energy processes in the scenario, but also disambiguating matter and energy. When Dan attempts to incorporate the idea of collisions between molecules with a 'double-high-five' interaction between himself and Andy, Andy and Denise object, probably because Dan lapses into identifying with the particles instead of the energy. In this case, this lapse is probably attributable to the visual salience of the 'purple balls' representing the gas particles in the displayed simulation. The participants and the balls look alike in certain ways: there are many of them, they are moving, they are inside a bounded region, etc. However, their similarity of appearance is accidental, and not the result of human cognitive activity deliberately constructing their similar appearance in order to communicate a deeper, more abstract likeness, as is the case in the relationship between persons and energy units in the design of Energy Theater. In other words, the participants and the balls have an outer-space vital relation of *similarity*, but the similarity is not a compression from *analogy*. Many Energy Theater participants have been observed to treat matter and energy interchangeably at first

(Scherr et al., 2013). Energy Theater contributes to the disambiguation of matter and energy by encoding a distinction between material objects and energy: energy (represented by participants) is located in objects (represented by areas demarcated by loops of rope). The energy in a scenario is clearly distinct from the objects (i.e. participants stand within, but are not mistaken for, areas inside loops of rope). The activity of developing an Energy Theater enactment for this scenario causes the group to attend to distinctions between matter and energy. As explained above in the section 'Research Methodology', we understand the process of participants enforcing the rules of Energy Theater as a major contribution to the learning of physics that is achieved during Energy Theater.

Identifying Energy Transfer

In this next episode, which follows soon after the episode above, one teacher (Sally) leads a discussion (see Figure 3) establishing that since the temperature of the gas increased during compression, there must have been a transfer of energy to the gas. Her model contrasts with June's model, which attributes increased temperature to transformation of internal energy in the gas. Sally accomplishes this by adding the vital relation of *identity* to units of energy. This episode is almost 4 min long (see Supplemental data) (Table 2).

The theme of this episode is captured by Sally's climactic question, 'Where is the energy coming from?' The question is clearly in accord with the Energy Theater

Figure 3. Participants negotiate Energy Theater for adiabatic compression of a gas. In this episode, participants establish that since temperature of the gas increased during compression, there must have been a transfer of energy to the gas

Table 2. Participants' speech with a description of the embodied action that accompanies it

Speaker	Speech	Embodied action
Sally	So here's my question, 'cause this is the one that I'm like y'know, I'm NOT productively stupid with this one	
Group	Laughter	
Sally	This—the speed of the molecules is constant right now, it's 300 K, right?	Turns to the screen and points at it
Andy	Mmm-hmm.	
Sally	'Cause that's what this is, a measure	
Scott	Yes.	
Elaine	Yeah, it's an average, but ==	
Sally	Right, the temperature?	
Elaine	==it's a constant average. It's an indicator	
Sally	Are we agreeing . . . When we squish the box the temperature goes up so the speed of those molecules has changed. Is that correct?	'Squeeze' Raises hand vertically with palm face down Petting motion—palm of right hand mostly vertical, also perhaps like a gentle 'halt' gesture
Group	Yes. It's true.	
Sally	Stop. That's what I . . . But then once the box stops squeezing, they stay the same speed after that Correct?	'Halt' gesture: Holds single palm vertically Facing palms to show box 'Stay' gesture: Places palm facing forward and down
Group		Nodding
Sally	Now. [Dramatically] Where is the energy coming from? Is that box losing heat. Energy.	'Window-wiping' gesture: Two palms forward, moving out and down, followed by 'halt' 'Rodent' gesture: Holds hands together as though a rodent holding food Adapts 'rodent' to point to simulation Slaps own right cheek several times quickly, as if to reprimand herself for using the word 'heat' improperly
Elaine	In the, in the, in the volume change?	
Sally	Are we saying 'here, I have this molecule with all this kinetic energy and it's the same amount of energy,' right? Now, somewhere in the proces we said that heat energy is going to be produced Is heat energy being produced?	Steps into rope 3 Performs group's iconic gesture for kinetic energy, 'Choo-choo' gesture: bent arms pump like the connecting rods of a steam locomotive 'Inclusion' gesture: Spreads hands outward 'Choo-choo' 'Choo-choo'
Andy	Yes.	
Sally	So, is the heat energy the same as the kinetic energy?	'Choo-choo'

(*Continued*)

Table 2. Continued

Speaker	Speech	Embodied action
Scott	The	
Sally	That's myyyyy Right?	Slowly throws hands up into the air
Scott	OK, I think what we gotta think about is that—what—I'm going to change what I said earlier. 'Cause I was saying, and you know, just the wall moving is going to provide some, and the banging into each other is going to provide some. I actually, I'm going to change that. I think it's, because that wall is difficult to push	Sally steps out of ropes 'Passage' gesture: Even sweep of both arms toward rope 3 'Push' gesture: Lines up arms with edge of rope 3 as though to push on the side of the container and compress the gas
	Because of the pressure that's inside there, I think that it really is providing All of that heat energy, that added heat energy must come 'cause this is the only input of energy is this wall moving.	Diminished 'Squeeze' Diminished 'Push' Points to rope 2 'Receive' gesture: holds upward facing palms toward rope 2
	So that kinetic energy going in there and squeezing that—that — volume of air, that space, it's the only input of energy in, so it must be	'Passage' 'Snowball' gesture: Two hands pack material into a small ball
Sally	It's giving it more kinetic energy to the molecules	

metaphor: specifically, not only does energy come from somewhere, but it is of great importance to know where it came from. To prioritize this question is to prioritize the vital relations *space* (energy has location), *time* (energy events are sequenced), and *identity* (energy can be identified and tracked) in a particular pattern that expresses local conservation. The *identity* vital relation is implicated with Sally's use of the word 'the' in 'the energy'; her perspective assumes that energy can have an identity, and that it is meaningful to ask about 'this energy' versus 'that energy'. By adding the vital relation of *identity* to units of energy, participants are encouraged to search locally for mechanisms of transfer.

The follow-up question 'Is the heat energy the same as the kinetic energy' is of comparable importance within the metaphor, since the forms of energy should be understood clearly and distinctly in order to correspond with observational evidence. In

particular, observing that a system is hot is not exactly the same as observing that it is fast. Thus, for the group to agree that heat energy (of the gas) and kinetic energy (of the molecules) bear a kind of identity relation requires them to recognize the transformation of the observation depending on its scale; a 'microscopic' observation would see the fast molecules, and a 'macroscopic' one would see a high temperature reading. In a manner similar to a conductor of an orchestra, Sally dramatically leads the group to consider her questions by eliciting the group's assent to various statements of phenomenological fact about speeds of molecules and temperature readings. Scott's response to Sally's questions is a mixture of phenomenological statements ('that wall is difficult to push') and gestures (squeezing and pushing) and ambiguous Energy Theater metaphor-style statements ('kinetic energy going in there and squeezing that volume of air'). Despite its lack of focus, however, Sally seems to use his input to conclude a clear statement of transfer of kinetic energy from the wall to molecules.

Representing Energy as Conserved

Interactions immediately following the previous episode establish energy as a conserved quantity, one that increases through a mechanism of flow and under a constraint of constant total amount, rather than through other means such as additional activity. This progress supports the group in theorizing about mechanisms of transfer and modeling energy as a discrete quantity. The group accomplishes this intellectual progress by negotiating different members' improvised variations on the Energy Theater blend (Table 3).

At the end of the previous sequence of action, Scott had suggested that energy is transferred from the wall to the molecules ('this is the only input of energy is this wall moving'). In the present sequence, Sally explores how this input is properly represented in the Energy Theater space. She tries out two different, and almost simultaneous, ways of imaging this energy input. First, she tries modifying the group's iconic gesture for kinetic energy (the 'choo-choo' gesture, simulating the pumping action of locomotive wheels with bent arms pumping forward and backward close to the body) to have faster arm movement. This proposal suggests a correspondence of speed (of molecules) with speed (of her arms). Sally's proposal is enacted, not declaimed; that is, it is not accompanied by any directly corresponding speech like 'Should I move my arms faster to show more kinetic energy?' Very shortly after this first proposal, she asks if her size should increase; she asks both with her words and with a gesture that encircles her body as though to trace out a larger person. This suggestion (increase in size) is a correspondence between speed and continuous spatial extent, as though the energy were more of a continuous mass than a multiplex of many individuals (Lakoff, 1987). Andy responds to Sally's question about size by with a definitive 'no' and prepares to act out the transfer of additional energy units to the molecules. Sally catches on ('So there's more of us in here?') before Andy or anyone else actually enters rope 3, representing the molecules. This conclusion is further affirmed verbally by Sally as she, Andy, and Scott act it out.

Table 3. Participants' speech with a description of the embodied action that accompanies it

Speaker	Speech	Embodied action
Scott	Yeah, and, and—	
Sally	But also at the same time, we've got this temperature going up, which I'm hearing people saying is a measure of an increase in heat energy. OK? So my question is	
	[chuckles] … 'Cause I can't see us	Steps into rope 3, steps backward into rope 2, and then forward into rope 3
	So then here I am	'Choo-choo'
	and this box gets smaller	Faster 'choo-choo,' about twice the previous rate. Uses cupped hands to trace a circle centered on
	when did I just get … Did I increase in size?	her torso
	Kinetically?	
	As a kinetic energy packet?	Arms down, hands slide laterally in and out
Andy	[Definitively] No.	Points to Sally
	So you're—so you're in here	Points to rope 3, steps back to rope 1
Sally	So there's more of us in here?	
Andy	Yeah, yeah. Scuba Steve pushes the wall and so he's using his muscles, to do this	Pretends to be Scuba Steve and push wall inward
	and then we join you.	Drops arms suddenly, does 'choo-choo' as she jogs from rope 1 to rope 2 to rope 3 as energy unit
Sally	dah dah dah, dah dah dah	Sings along with Andy's motion
	So there's more packets of kinetic energy ==	
Scott		Steps into rope 3, rubs his palms together (group iconic gesture for thermal energy), changes to 'choo-choo' when Sally says 'kinetic energy'
Sally	== that's being used by the molecules.	

In all three manners of enactment, energy is shown to increase: faster arms, larger body, and more persons. Is the progression toward representing more energy with more persons in this episode genuine intellectual progress or is it merely greater adherence to the arbitrary rules of the Energy Theater 'game'? For two reasons, we believe the progression of action is substantial intellectual development. First, only in the 'more persons' version of 'more energy' is the energy increase shown to result from the transfer of energy from one object to another. When arms move faster, or a person is imagined to grow larger, the energy might be shown to be increasing, but it is not shown to increase through a mechanism of flow or under a constraint of conservation. As we have shown previously (Scherr et al., 2013), the movement of

persons to model the flow of energy leads naturally to learners considering the mechanisms and reasons for the flow of energy, which we believe is a more advanced level of analysis. In the present episode, the mechanism of energy transfer (the 'wall' or piston pushing on the molecules) is discussed verbally, but the link between the pushing and the energy flow are enacted explicitly only at the end, by Andy. Notice that Sally says 'It's giving it more kinetic energy to the molecules' after Scott explains the idea of energy flow verbally but appears not to appreciate the meaning of her own use of the word 'giving', that is, that energy flows from the wall, until Andy prepares to act it out by highlighting 'you're in here', and stepping back to rope 1. Thus it appears, in this situation at least, that the symbolic enactment of energy transfer through body motion is more effective at communicating the idea of flow of energy than verbal descriptions. One explanation in terms of blending is that Energy Theater, through its multi-modal nature, is the most efficient blended space for coordinating the many vital relations that concern us when explaining physical processes in terms of energy.

The second reason that we believe representing more energy with more persons is an intellectual advance for the group is that the transfer of logic from discrete domains to continuous domains has been shown to be generally more successful than the reverse (Bassok & Olseth, 1995). Setting aside the issue of whether energy is *actually* discrete or continuous, we recognize the importance in science of being able to model energy as either. If learners need to be able to model energy as continuous, it is better to practice modeling it as discrete, since the transfer from discrete to continuous is easier. Reasoning about continuous quantities has also been shown to be more successful when those quantities are parsed, or discretized (DeWolf, Bassok, & Holyoak, 2013). If 'more energy' were shown with more motion, or by imagining a bigger person, it would not be parsed, and so would not support the development of quantitative reasoning about energy.

Finally we discuss Andy's dual-role enactment first as Scuba Steve and then as an energy unit. Responding to Sally's 'Did I increase in size?', Andy moves over to rope 1, describes and copies Scuba Steve's actions, and then immediately changes her role to be a unit of kinetic energy that transfers from Steve, through the wall, and to the balls. First we notice that there are no objections by the group to Andy 'breaking character' as an energy unit to pretend to be an object in the scenario; nor is there any evidence of confusion as a result of Andy switching roles. On the contrary, Andy's actions are likely understood by the group as permissible, clear, and helpful; Sally, at least, appears to be satisfied with Andy's explanation. The situation poses a challenge to an analysis of the situation in terms of blending because of the apparent lack of consistency in the correspondence between the input spaces 'people' and 'scenario'. Our analysis is that Andy successfully and rapidly communicates the temporary engagement of a different identity (one for which she is blended with Scuba Steve) through her word choices and body action, and then similarly re-engages the Energy Theater blend by picking up the energy unit identity. Andy initiates the alternative blend between herself and Scuba Steve with the contrast in grammatical designation of Sally, using the second person 'You're in here', and herself, referring

to herself as 'Scuba Steve' rather than 'I.' Through this choice of words, she indicates that she is something other than herself, or other than that with which her self has been blended thus far—namely, a unit of energy. When she is finished showing what Scuba Steve does, she becomes herself (that is, defined contextually, as blended with energy) again, which she indicates by referring to herself in the first person, saying 'we join you'. The change in role is also indicated with body action: As Scuba Steve, Andy holds her arms up as though she were pushing on large handles, imitating his body position, as visible in the simulation projected behind her. When she is finished showing what Steve does, her body position changes quickly—perhaps to communicate a discontinuous shift of identity—to begin a slow jog from rope 1 to rope 3, with her arms sustaining a continuous 'choo-choo' to communicate her identification with a unit of kinetic energy, while saying 'we join you'. Contrast this entire role-switching process with Dan's failed attempt to show an increase in pressure with double-high fives at the end of Video 1: Dan uses the first person 'we', formally proposes the action 'But what if we … did this', and marks the proposal as symbolic by saying 'for pressure'. His bid is declined by the group because it is understood as an action proposed within the Energy Theater blend and with the same identity he had when he proposed the man-wall-balls pathway (rather than one in a blend running in parallel, in which he has an alternative identity) and as one that does not follow the Energy Theater blend's rules.

Conclusions and Implications for Instruction

Our analysis of learner interactions during Energy Theater shows general agreement between the theory of conceptual blending and our observations. In particular, adult teachers-as-learners appear to find the blended space of Energy Theater to be usable, sensible, and productive. Further, the structure of the blended space appears to facilitate meaningful intellectual exchanges about the key features of energy dynamics, both in the gas compression scenario we studied here, and in other scenarios as we reported previously (Scherr et al., 2013). We note that in this study, in which we set out to analyze Energy Theater in terms of conceptual blending, we were compelled to analyze not only the planned, prescribed blend structure of Energy Theater, but also many improvised learner interactions that, in varying degrees, borrowed from, or varied from the prescribed blend, but which in any case had some significant blend structure. The intellectual work accomplished by learners in our study appears to have proceeded in large part through these improvised actions. We believe certain features of the design of Energy Theater promote these productive improvisations: rules that provide sufficient initial structure to the space and that generally promote multi-modal action, and, balancing the rule structure, plenty of opportunities for freely chosen action. Therefore, to those readers who would design similar activities for promoting science learning through blending and metaphor, we recommend that special attention be paid to the balance between rules and free choice that is characteristic of structured improvisation.

We aim to promote Energy Theater as a valuable classroom learning activity for teachers and students from young adolescence to adulthood in all science disciplines. Our hypothesis is that teachers and students that use Energy Theater will more reliably conserve energy as they track its transfers and transformations among objects in a system, and that Energy Theater does so through its leveraging of some fundamental cognitive patterns of conceptual blending.

Our work demonstrates the instructional effectiveness of Energy Theater with a small number of adult learners. Further research is needed to examine wider implications for practice. For example, future investigations might use methodologies similar to ours to study *student* learning as a result of Energy Theater, or use larger-scale methodologies (such as survey instruments or written assessments) to study the learning of larger numbers of teachers and their students. We also hope to conduct studies of what scaffolding is needed for younger learners to engage meaningfully with Energy Theater. Such investigations will inform the development of classroom practices that greatly enhance the learning of energy conservation and tracking.

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Supplemental data

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Notes

1. Some of this material appeared previously in Scherr et al. (2012).
2. See Amin (2009) for more examples of the manner in which Feynman speaks metaphorically about energy.

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