Modelling instruction for university physics: examining the theory in practice

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Abstract
In spite of a lack of consensus about the nature of scientific models, the role of models and modelling are well established in the practice of science. Students who participate in developing, validating, deploying, and refining models are engaged in authentic scientific practices. Modelling instruction (MI) was developed to promote the role of models and modelling in introductory university physics classes. MI for university physics is founded on the basis of two theoretical foundations, modelling theory of science and modelling theory of instruction. We claim that the translation of these theories into classroom practice supports learning in science. We substantiate this claim by first describing how these theories establish complementary cycles of content development and student participation. Then we provide evidence of these interacting cycles by analysing the development of a conceptual model in a MI university physics class using video data. The video data we present includes students developing a scientific conceptual model first in a small student group and a later in the full class. We argue that the integration of the theoretical components underlying MI are key supports in providing the opportunity for students to develop conceptual models and engage in the practice of doing physics.

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Introduction

Active learning pedagogies have been shown to be more effective than lecture approaches (Freeman et al. 2014). Current research trends are moving away from comparisons of active learning to lecture and toward investigations of how active learning instructional practices achieve these outcomes. Further, elaborating differences among instructional approaches will build greater understanding about the relationship between practices and outcomes. Modelling instruction (MI) is one version of an active learning instructional practice developed for university physics.

Historically, the implementation of MI has shown positive effects for students in introductory physics classes at Florida International University. Work examining the impacts of MI has shown it to be effective at improving the conceptual understanding of physics when compared to traditional lecture classes (Brewe et al. 2010), moving students toward more expert-like views on the nature of science (Brewe et al. 2009, 2013), and positively impacting students’ views of their own capability and success (Sawtelle et al. 2010, Goertzen et al. 2012).

However, none of these works have unpacked how the design of the learning environment contributes to positive outcomes. In this paper we set out to describe how the theories of science and epistemology that guided the development of curriculum and pedagogy play out in terms of the development of content and the classroom interactions. These events in the classroom play out to create opportunities for students to engage in doing physics.

MI is a reformed curricular and pedagogical approach to physics that centres on the development and testing of conceptual models. The reform effort can be described as the intersection of two intersecting cycles; a cycle of content development known as the modelling cycle (Wells et al. 1995, Brewe 2008), and a pattern of classroom interactions guided by the modelling theory of instruction (MTI) (Hestenes 1987, Wells et al. 1995, Desbien 2002, Halloun 2004, Durden et al. 2012, McPadden et al. 2017 this volume). The modelling cycle derives from the modelling theory of science (MTS) which posits that practicing scientists actively engage in the development and deployment of scientific conceptual models (Hestenes 1987, Halloun 2004). MTI helps to establish a pattern of interaction within the classroom. Together, these theories address the questions ‘What is science?’ and ‘How can we engage students authentically in learning science?’

One of the distinguishing features about MI is that it includes both curriculum materials and pedagogical designs. Other reforms tend to focus on either the instructional practices without a sharp focus on the curricula, or how the content is developed without explicit focus on the pedagogy. Examples of the former include guided inquiry, model-based reasoning (Windschitl et al. 2008) and peer-instruction (Crouch et al. 2007); examples of the latter include studio physics (Wilson 1994), and SCALE-UP (Beichner et al. 2007).

In this paper, we elaborate on how MI develops through the modelling cycle and the MTI and then examine how a model building event plays out in the learning environment. From this, we argue that students in the MI classroom successfully build a conceptual model through MI, engaging them in the process of doing physics. We explore in this paper how a curriculum designed to make explicit the roles of models and the processes of building, validating, deploying, and revising models contributes to successful learning in physics and consider how this leads to the positive learning outcomes that are prevalent in MI.

Modelling as the central practice of science

The MTS averrs that modelling is the central activity of science (Hestenes 1987, Halloun 1996, 2004, 2007, Giere 2005). As such, MTS can be seen as a semantic view of
scientific theory (Adúriz-Bravo 2013). According to MTS, science can be seen as progressing through the iterative process of building, validating, deploying, and revising conceptual models (Brewe 2008). Where a conceptual model is a purposeful, coordinated set of representations of a particular class of phenomena that exists in the shared domain of discourse and is an inscription of disciplinary knowledge. Attention to models and modelling are not novel in science education; a variety of researchers have proposed that modelling is essential to developing understanding (Greca and Moreira 2001, Knuuttila 2004, Koponen 2007, Windschitl et al 2008, Passmore et al 2009, Schwarz et al 2009, Louca et al 2011, Passmore and Svoboda 2012). The framework for science education standards cited ‘developing and using models’ as one of eight essential practices for scientists and engineers, stating that ‘Models make it possible to go beyond observables and imagine a world not yet seen.’ (National Research Council 2011).

This central practice of conceptual model building establishes how the content of a science course should be organised and developed. Any number of curricula can organise the content of a course around the practice of modelling, and many do, including those advocating model-based inquiry (Clement 2000, Lehrer and Schauble 2006, Windschitl et al 2008) or learning progressions for modelling (Schwartz et al 2009). In university physics, Spiral Physics, Matter and Interactions, CLASP, and P3, incorporate elements of modelling (D’Alessandris 2007, Potter et al 2014, Chabay and Sherwood 2015, Irving et al 2017).

**MTI focuses student participation**

A straightforward extension of the MTS is that if science progresses through model development, validation, deployment, and revision, then students should be engaged in learning to develop, validate, deploy, and revise conceptual models. This extension is the MTI and is one of the features of MI that distinguish it from other model-centred instructional approaches. MTI makes MI distinct because MI integrates a pattern of participation in classroom activities.

MTI is an epistemological framework for engaging in meaningful science learning (Clement 2000, Halloun 2007). MTI implies that learning science is a necessarily active practice, in which students engage in the activities of science and develop skills, expertise, identity, and membership which shapes their continued participation. This framing of learning is consistent with framing learning as an ongoing transformation of participation. Rogoff (1990) describes such a participationist framework as an apprenticeship in thinking. Rogoff argues that because people are constantly participating in social interactions, their participation continually feeds back into their understanding of the world, which, in turn, influences how they participate in future social activities.

The MI curriculum and pedagogy co-developed to promote productive participation in modelling. While the content develops through the modelling cycle, MTI guides the participation. Learning happens as students interact with other students, with the course materials, and with the instructor. For example, as students move through a content cycle of model building, testing, deployment and revision, the instruction is designed to have them work in small groups on shared whiteboards, which then are presented in ‘board meetings’. During the small group sessions students are building models by learning to use and interpret representational tools, to solve problems using these tools, and to relate the representations to physical phenomena. Board meetings happen when a number of small groups gather to discuss their whiteboards. These board meetings are times where students aim to explain their efforts during small group work, question other groups, and ultimately to reach consensus.
about how to model the situation. The interplay of small group work followed by board meetings is the primary mode of instruction and happens typically once per class meeting if not more frequently.

Throughout this process the instructor plays critical roles. Overall, the instructor is the disciplinary expert and uses this expertise to purposefully choose activities, guide student inquiries, and curate discussion. Prior to any instruction taking place, the instructor chooses or designs activities for students. The choice of activity is critical and should be both responsive to student progress as well as attending to time. As students work in small groups, the instructor keeps track of what different student groups are doing, what ideas are being developed, and what questions are likely to arise during the board meeting. During the board meeting, the instructor’s role is to facilitate the discussion, aiming to arrive at consensus that is consistent with the disciplinary knowledge.

The role of the instructor is complex and adaptive. Desbien established a set of instructional moves, strategies, and heuristics that can be used to help facilitate the discourse in a MI classroom. These moves, collectively known as modelling discourse management, were further expanded by Durden et al. (2012).

Research into teaching and learning from a participationist perspective involves investigating the unfolding of events in a context-laden learning environment. The MI learning environment is a complex dynamical system, and requires a broad perspective that attends to the activities, organisation, curriculum, and pedagogy, as well as to the instructors and students.

Examining theory in practice

The central practice in MI involves the building of a scientific model. This process is a complex social phenomenon. To analyse a model building event, observable features such as the students, instructors, activities, and artifacts are important. However, contextual elements that are not directly observable but are equally important, are often inferred. These contextual elements include answers to questions like ‘What do the participants see as the meaning and purpose of the activity?’ and ‘How are the goals of curriculum and pedagogy conveyed through the activity?’

We are interested in the ways in which people participate with the tools of the discipline, whether they take up the established purposes of the curriculum and pedagogy, and how their participation supports the goals of the curriculum and pedagogy. This has specific methodological implications when attending to the unfolding of events in the learning environment. We will be looking for the development of conceptual models in the actions of participants.

Drawing on the participationist perspective, our research attends to the design and implementation of the pedagogy, curriculum, and organisation of the MI learning environment. As a result, we do not attempt to separate analyses of students, teachers, curriculum materials, and the learning environment. Instead, we carry out event-analyses of a MI class. Rogoff (1990) proposes seven basic premises for carrying out event-level analysis. 1. Change is assumed to be basic; the goal should be to understand processes. 2. Events and activities are organised according to purposes or goals. 3. Meaning and purpose are central to defining an event. 4. Cognitive processes are essential components of purposeful action. 5. Thinking cannot be separated from the goal and circumstances of the action. 6. Human action and thought are a function of biological and social inheritance. 7. Variability is central in the processes of development; developmental work examines the coherence of developmental progress within a group in accordance with locally defined goals.
Data collection and analytic method

We take the event as the unit of analysis. Rogoff (1990) describes this choice as providing the opportunity to consider the event as a whole rather than a sum of individual parts. In doing so we assume that change occurs, and the focus is on understanding the process of that change. Our data collection and analysis centres on defining the boundaries of an event and understanding the process by which that event unfolds. Our goal in completing this analysis is not to argue that MI ‘works’ per se, but to describe how a theoretically-driven description of a curriculum plays out in a setting that engages students in a sophisticated process of doing physics.

Data collection

The data included in this paper comes from a semester-long project to video-record the MI classroom. We had Institutional Review Board approval to carry out the data collection and all students featured in these analyses have signed informed consent documents. The MI classroom consists primarily of 30 students broken into groups of 3–4 who work together on individual assignments before coming together to meet in whole class discussions (board meetings). The data collection process involved video-recording two small student groups for each class meeting and positioning two video cameras on either side of the large group board meeting. In this way, the primary components of the MI classroom were captured including conversation in small groups, the transition from small group to large group, and the large group discussions.

This paper focuses on data from two consecutive class meeting days. The first day the students worked in small groups on investigating the ball bounce activity (see supplementary materials available online at stacks.iop.org/EJP/39/054001/mmedia for actual copy of the activity). The ball bounce activity required students to bounce a playground ball with a motion detector positioned directly above the ball as it bounced several times on the ground. The playground balls provided were slightly deflated in order to ensure that the ball did not bounce back to its initial height. The activity asks students to compare their predicted set of position versus time, velocity versus time, and acceleration versus time graphs to those generated by the motion detector and the software system Logger Pro. The activity then asks students a series of questions to have them consider which basic models they have previously developed that can describe the motion of the ball.

The key in this process is that up until this point the students have investigated only constantly accelerated motion, and the moment when the ball hits the floor does not follow this basic model (as the ball quickly changes directions). The final question in the activity —‘Can you explain why the ball doesn’t bounce as high?’—is intended to guide the students to the conclusion that they need a new element in their model to describe this motion. However, the activity does not guide them to develop this new element, which is instead left to the instructor(s) in the classroom. The instructor guides the students to discuss energy and energy representations that describe why the ball does not reach its initial height.

Up to this point in the course students have developed a constant acceleration basic model that is both descriptive and predictive. The pedagogical goal in this sequence is for students to adapt their existing models to include energy conservation. In the modelling cycle the goal is to refine the constant acceleration basic model to include laws, such as energy conservation, by asking the students to describe a physical phenomenon with characteristics that cannot be described using the representations they have developed thus far.
The data we present focuses on a pie chart representation of energy. Pie charts are intended to convey a substance-like metaphor for energy (Brewe 2011, Scherr et al 2012) with an emphasis on energy conservation and the storage and transfer of energy. The utility of pie charts is discussed more extensively elsewhere (Brewe 2011). In our data we primarily attend to two aspects of the pie charts. The first is that the size of the pie chart indicates the amount of energy in the system: if the energy remains constant in the system, the pie chart should not change size, but if energy transfers out of the system, the size of the pie chart should decrease. The second feature focuses on the tracking of the storage of energy in the system: the size of a wedge in the pie chart indicates the amount of energy stored by a particular mechanism (e.g. kinetic or potential). We provide examples of the various pie charts that could be used to describe the ball bounce activity in figure 1.

Data analysis

The data come from the interactions that students in a small group (Amy, Marcus, and Kurt) have with two instructors on the first day and with members of the rest of the class on the second day. All of the interactions are the result of working on an activity that challenges them to understand and explain why the ball does not bounce as high. There are two instructors in the classroom maintain parallel interactions with the students, but have differing power relationships. One instructor, referred to in the data below as Professor, is the lead instructor in the classroom. The Professor had 6 years experience teaching with the MI materials and has documented success in impacting both students’ conceptual ideas about physics and their attitudes about science. The second instructor, referred to by the name Lara in the data, is an undergraduate physics major who took the MI class the previous year and who serves as an assistant instructor in the classroom. While we distinguish in the data that follows between the Professor and Lara, we note that the students see them both as serving the role of an instructor. We present a series of four clips from the first day when the students had completed the activity (but are being pushed by the instructors to represent the energy in the situation), and then present a series of three clips from the second day when a board meeting takes place with students presenting whiteboards to the large group.

In the analysis that follows, we describe the process by which the students adapt their conceptual model to incorporate the pie chart representation of energy by working through the ball bounce activity (Brewe 2011). The ball bounce activity starts at a point where students have only the kinematic models of constant velocity and constant acceleration in their toolkit. The instructional goal of this activity is to introduce the concept of energy as a modelling tool that can be used in regions of non-constant acceleration. MI explicitly introduces the representation of energy pie charts to facilitate students’ early thinking about energy concepts. Target goals of this activity include (1) introducing energy as a concept into the model; (2) unpacking the difference between the total energy in the system and storage mechanisms of energy; and (3) developing energy pie charts as a representational tool.

In the analysis we use clips 1–4 to describe how the modelling cycle supports students in developing a conceptual model that highlights the important goals of the activity. We then argue that the conceptual model is developed and appropriated by other students in the class during a large group board meeting in clips 5–7. In presenting this analysis, we aim to describe the process by which the elements of the learning environment MI interact and provide opportunities for students to appropriate the development of the conceptual.

We focus on understanding the process of the conceptual model development. In doing so, we do not claim that the event we have chosen is descriptive of how all student groups developed the pie chart representation, but instead recognise the importance of focusing on
the coherence of a single story with locally defined goals between the students and the instructors. As such, we do not attempt to describe all the progress of all groups (or all students in the class), but rather attend to the set of students who interact with the development of the model in a locally defined way.

**Analytic method.** In the following event-analysis, we consider how each sequence in the event contributes to the development of a conceptual model that includes energy, and the appropriation of the pie chart representation. In keeping with the premise of event-analysis
(Rogoff 1990), our goal is to describe how the theoretical underpinnings of MI combine in an event in which students make productive progress on developing a conceptual model. To this end, we structure our analysis in a sequence of events that follow the development of the model. In each sequence we unpack both where the students are in the development of the model and how the elements of MI play out in those moments. We do not aim to claim that all moments in MI look like the sequence discussed here, nor that MI causally created this sequence of events. Instead, our goal is to understand the process by which this event unfolds and how MI contributes to the process.

Analysis

We have chosen to focus on these particular clips because they connect well with the goals laid out in the ball bounce activity. Additionally, this sequence of days provided a clear path to follow in the conceptual model development. However, we have left a significant portion of the talk out of the following clips. Whenever we do this we will briefly describe the intermediate time chunks, and provide an estimate of how much time was cut from the transcript. We number the turns consecutively to indicate the connection between the discussion from one clip to the next.

Day 1: The small group constructs the conceptual model

We enter the data after the small group of Amy, Marcus, and Kurt (all names are pseudonyms) have completed all of the prompts in the ball bounce activity, and the instructor has just arrived at the small group table. Prior to the beginning of this transcript, the instructor had been working with a different small group across the room, and Amy, Marcus, and Kurt have been sitting quietly.

Clip 1: Introducing the ideas of elasticity and energy

1Professor: So why doesn’t the ball bounce as high?
   {pause}
2Kurt: Whatever distance it travels, every time it bounces, it’s going to go as high as it did before. It’s going to have the same amount {inaudible}.
3Amy: But remember, this is being dropped by, because the person drops it…
4Marcus: The ball isn’t 100% elastic so you won’t get back all the energy you had going down. Does that make sense?
5Prof: I don’t know, I didn’t hear what you said.
6Marcus: I said the ball isn’t totally elastic. So it won’t reflect the energy that it had coming down. For it to go back up.
7Prof: What was going down?
8Marcus: Energy.
9Prof: OK.
10Marcus: Won’t be the same coming down. The potential energy that it had when it comes up is the kinetic energy when it comes down. But because it’s not totally elastic it will lose some of the energy, and so it won’t go back up as high.
11Prof: Where’s that energy go?
12Kurt: Into the ground.
13Marcus: The ball absorbed it.
Kurt: I dunno.
Marcus: Yeah, cause it’s the ball that loses the energy. The ball that absorbed it. The ball isn’t firm or anything.
Amy: Yeah, it’s a really soft [inaudible] ball.
Marcus: Like the more elastic the ball itself is, the material of the ball, the better it will actually be for it to bounce off the ground.
Amy: Go back up to the same height.
Prof: OK, so...
Marcus: It wouldn’t go to the same height, because most of the gravitational…
Kurt: It would go a lot higher than it does now.
Marcus: Yeah.
Amy: So you’re saying the elasticity of the ball, and then…
Marcus: The elasticity of ball and then…
Amy: …gravity. Is why.
Prof: So you say it has energy when you start. And then when it gets to the ground what happens to that energy?
Marcus: It’s dissipated. Some is dissipated.
Prof: So, how can you show that?

This clip begins with the instructor prompting the group to think about why the ball does not bounce as high, which is a reiteration of a question in the activity they are working through. Kurt and Amy toss a couple of thoughts out onto the table (turns 2–3), Marcus brings in the idea of elasticity (turn 4), suggesting that the ball is not 100% elastic and that is why it doesn’t bounce as high. In explaining his ideas about the ball not bouncing as high, Marcus references forms of energy as kinetic and potential (turn 10), and connects the lack of elasticity to energy loss (turns 4, 6, 10, 17). The students initiate the use of the idea of energy (turns 4, 6, 8), which the instructor supports by asking, in turn 11, ‘Where did the energy go?’ Kurt and Marcus then provide two conflicting answers (turns 12, 13, 15). Marcus’ idea ends up winning out, as Kurt defers his statement with ‘I dunno’ (turn 14), allowing the idea that the ball or the material of the ball absorbs energy to take precedence (turn 15–17). Marcus attributes this absorption of energy to what he terms the elasticity of the ball, which Amy echoes and supports (turn 16). At the end of this initial clip, the professor tries to return the discussion to where the energy goes, but Marcus simply answers, ‘It’s dissipated.’ The instructor prompts the students to think in terms of a representation at the end of the clip by asking, ‘So how can you show that?’

While there seems to be disagreement about what the elasticity of the ball determines in this clip (see Amy, Marcus, and Kurt’s disagreement in lines 18–21), the conceptual model constructed in this initial clip includes the elasticity of the ball as an important player in telling the energy story of the ball not bouncing as high.

Clip 2: The Instructor introduces the pie chart representation

In the intermediary time between clips 1 and 2, the instructor leads the students to agree that there would be utility in having a representation that could show how the energy dissipates and why the ball does not bounce as high. During this exchange Marcus offers the formulaic reasoning of \( mgh \) for representing the energy, but when pressed for what evidence Marcus has for that expression Marcus admits he does not have any. Clip 2 begins with the professor introducing an alternative representation—the energy pie chart.
Prof: So one way you can represent it is with a, like a pie chart... So you can have a picture of a pie chart when you start, and then after it bounces...

Amy: Oh! It’s gonna...

Professor: …how big is the pie?

Amy: Ohh. Ok so like...

Prof: The pie would be probably be as big.

Amy: No. Some slices are coming off.

Prof: Or, and so you can show that...

(Cross-talk) Prof: …by making it… Amy: So then it’s eating these slices...

Amy: Smaller? Or do you mean cutting off pieces.

Prof: I would, probably making the whole thing smaller.

Amy: So, you’re saying...

Kurt: So...

Amy: … This is, this is my pie, this is the amount of energy I started with when I dropped it. And then as I, as it hit the floor, or whatever it is, it got smaller. And then that’s the first bounce, right? And then this would be smaller as it hit the second bounce. Is that what you’re saying?

Prof: So you could have, that could represent energy….leaving.

Kurt: Ok.

Amy: So this is...

Prof: And then you could think about what the slices in the pie mean.

Amy: I’m sorry, say that again?

Prof: What do the slices in the pie mean? Because he [Marcus] had some other words.

Kurt: Neanderthal?

[laughter]

Kurt: umm...

Amy: He said energy. ‘Cause that’s what we’re talking about.

Kurt: Potential energy and kinetic energy.

Prof: So, just before it hits the ground, does it have energy?

Marcus: It does.

Kurt: Yeah.

Amy: Yeah.

Prof: What kind of energy does it have?

Marcus: It’s all kinetic.

Prof: It’s all kin…it’s motion energy.

Prof: So, was it moving when it was up here in your hands?

Marcus: Nope.

Amy: [shakes her head no] It had potential.

Prof: It must have had some different kind of energy.

Marcus: It has potential.

Amy: Potential energy. It has potential to {inaudible}

Prof: Well, so…it seems to be coming from gravitational.

Amy: Say that again?

Prof: So maybe some kind of gravitational energy.

Amy: OK, but it’s in your hands.

Prof: Yeah. Before it starts moving. Just as you release it. It has some kind of energy…what must be happening to the energy as it goes from one point to the other.

Kurt: It goes down.

Prof: Just before it hits the ground.
Amy: I’m sorry?
Prof: [to Kurt] What were you saying?
Kurt: Wait, would the energy increase? Or would it be constant? Yeah, it would be constant wouldn’t it?
Prof: Before it hits the ground, what should happen to the energy? Should it be constant?
Kurt: It should be constant. I was thinking potential energy. So, right before it hits the ground.
Amy: Or is it constantly decreasing? Because what you’re saying is when it hits the ground the energy’s...
Prof: Yeah, but it’s speeding up.
Prof: But you’re saying it’s speeding up. Are you saying it has less energy when it’s moving faster?
Marcus: It’s a different type of energy.
Amy: Yeah?
Prof: It’s a different type. So you have types of energy.
Marcus: It’s like this…
Prof: So, you could like make some diagram that has, you know, circles and pies, and things changing. Like you could take a snapshot just as you drop it, just before it hits the ground, after it hits the ground.

In clip 2, the instructor presents the idea of a pie chart as a way to represent the energy of the ball as it falls and bounces, particularly focusing on the size of the pie (turn 29). Amy reiterates the idea relatively quickly and vocalises the sense of the pie as getting smaller or that the pieces are coming off (turn 34, 37). The instructor prompts them to consider what the slices would represent and calls their attention to the ideas Marcus presented in the previous clip (turns 45, 47). Amy recalls that Marcus was talking about energy (turn 50), and Kurt refines the idea to potential and kinetic energy (turn 51). The instructor then asks them to consider how the potential and kinetic energies would look different throughout the motion of the ball (turns 52, 56, and 59), implicitly prompting the students to account for energy transfer in their representation.

As a group, they reach a consensus that there is potential energy at the top, and there is some kinetic energy just before it hits the ground (turns 56–64). In turns 74 and 76, Kurt seems to struggle with whether the energy should be constant or changing, but it is unclear from his talk whether he’s struggling with ideas of total energy or forms of energy. Amy echoes Kurt’s confusion about the energy change (turn 77), with the professor articulating the contradictions (turns 78–79). At the end of the clip, Marcus offers that there are different types of energy (turn 80), which may help resolve Kurt and Amy’s conflict. At the end of the clip (turn 84) the instructor notes that this representation should account for ‘things changing’ as the ball moves through time, ‘like snapshots’. To be clear, the instructor does not give away the answer on how to construct this pie chart representation of the energy. Rather, as he walks away, the instructor assigns the students the task of developing a pie chart representation for the changes in the ball’s motion.

In terms of the conceptual model at this point, we have seen students working with ideas of energy change and energy transfer (clip 1) as they work towards explaining the phenomenon of the ball bounce. In clip 2 the students and professor work towards creating a representation of the energy change, and in doing so we see the refinement of ideas in terms of connecting particular energy statements to points in the path of the ball as well as bringing...
in ideas of forms and types of energy and talk about how the energy changes. Certainly the model the students are building is not yet well articulated, but we see several ideas on the table. We also note that both the activity and the prompts from the instructor are critical components of the discussion that took place in this clip. The activity was designed for students to need to grapple with why the ball does not bounce as high. In designing the task this way, the movement from kinematic descriptive models toward descriptions involving energy was motivated by the phenomenon the students were studying. Further, nowhere in the ball bounce activity is the idea of energy mentioned, but the task is designed in a way that the ball losing or transferring energy is a natural explanation for why the ball does not bounce as high. In this clip, we see the instructor cultivating this connection with the students, and suggesting a particular representation that he expects would be useful for telling the energy story.

Clip 3: Marcus and Amy discuss the professor ‘moving’ the idea

Immediately following clip 2 the group spends several minutes in off-topic conversation. Then Lara (the undergraduate Instructor) arrives and has a short discussion about other courses in the university. At this point Amy reinforces the conversation by saying, ‘OK, so why doesn’t the ball bounce as high? I agree with your [Marcus] elasticity thing. That makes sense.’ At this point the students and Lara have a meta-discussion about the ideas they have shared with the professor. Amy and Marcus contrasting the idea of elasticity with the representation of pie charts introduced by the professor. Marcus and Amy begin to express some frustration with why the idea of pie charts were ever introduced, ending with Marcus saying, ‘He [the Professor] distinctly moved my idea from using energy.’

In this intermediary time, this small group of students do not simply take up the representation offered by the professor; rather, they struggle with how their ideas of elasticity differ from the pie chart representation, and they express a frustration with the reframing of these ideas. As a group, they report to Lara that energy in pie charts is different than Marcus’ idea about elasticity and energy. The Instructor introduces the energy pie chart representation, however, it is not necessarily true that the students simply take up these ideas. It is fairly common practice in this classroom that the instructors probe the students’ understanding of the ideas, and allow the students to struggle through their reasoning rather than giving the correct answers. As we see in clip 3 often after the professor seeds a new representation or idea s/he will leave, allowing students the space to wrestle with the ideas.

Clip 4: The story of blue and brown pie: a conceptual model of energy

After clip 3, Lara asks the group to explain their elasticity model for a bit. During the omitted exchange, Marcus and Amy explain that energy dissipates from the ball because it is not perfectly elastic. Marcus spends some amount of time explaining how he believes the deformation of the ball connects to this idea of energy dissipation, and that the professor’s use of pie charts did not use the idea of energy at all. Lara focuses the conversation for a time on where the energy dissipates to and the students decide it goes to things like creating sound and heat. Marcus pushes the idea of deformation of the ball requiring energy, which brings the conversation back to what elasticity of the ball really represents. We enter clip 4 just as Lara asks the students to decide how they would model how the elasticity of the ball affects the energy and how high the ball would bounce.
Lara: OK, you say that about it, but how would you model it?
Amy: I’m sorry?
Lara: How would you model energy?
Amy: He’s talking about pies, but I don’t…it doesn’t make sense to me.
Lara: OK, forget that.
Marcus: But that’s exactly how you’re going to model energy. Through pies.
Lara: No, no. Forget pies. Because pies don’t make sense at this point. How would you normally model energy? Maybe it makes sense to you.
Marcus: What are you disposing the pie?
Lara: Okay, then. Make sense to me how you-
 Marcus: That’s the foundation of our theory right now. The energy that we have is in the size of a 12 inch pie. Right? When you drop this pie, okay?
Amy: Emotional.
Marcus: Its potential energy is 12 inches of pie. Right? And this 12 inches of pie is all movement types of energy, right? So, at this point in time it’s 12 inches of pie, potential pie, right? And I release it. So this pie is changing into kinetic pie. So you see, there’s brown pie and blue pie. And the brown pie, right? Potential pie. As it’s falling, it’s slowly changing to blue pie.
Lara: And then you have-
 Marcus: Because the pie fell. So we lose blueberry in sound, and we lose blueberry in heat, and we lose blueberry in all different forms of energy.
Amy: And then when it comes up, what the, what pie is it now?
Marcus: It’s still blue pie coming up, but as it goes up, it goes back into brown pie, So as it comes up-
Amy: Brown pie is kinetic pie? And then-
 Marcus: -potential
Amy: It is- no, brown pie is-
Kurt: -potential
Marcus: -potential pie.
Amy: Okay.
Lara: Wait, let’s define these types of words. So what exactly does potential or brown pie mean?
Marcus: All right-
Amy: Potential energy-
Marcus: -blue pie-
Amy: Blue pie -
Marcus: -is kinetic pie.
Amy: Okay.
Kurt: Kinetic pie.
Marcus: -kinetic energy.
Lara: How would you explain it to her given that she doesn’t know anything about kinetic energy?
Marcus: It’s the, blue pie is due to motion. And it is increasingly getting faster as it goes down.
Amy: Okay.
Marcus: So it’s increasing its kinetic, so it’s getting more blue as it goes down.
Amy: Okay. That makes sense.
Marcus: Right?
Amy: And then when it hits the ground it like-
Marcus: It’s all blue pie.
Amy: All over the floor.

Marcus: It’s all over blue pie.

Amy: Okay. So then when it comes back up-

Marcus: So as it goes back up,

Amy: it’s changing back to brown pie.

Marcus: it’s changing back to brown pie.

Amy: And that’s potential pie.

Marcus: And that’s potential pie.

Amy: And then-

Marcus: So when it reaches the, the-

Amy: The highest-

Marcus: The highest point, it’s peak-

Amy: So when it’s at its-

Marcus: -it’s all brown pie.

Amy: What?

Marcus: The highest point that it reaches at the top-

Amy: That’s brown pie.

Marcus: -it’s all brown pie.

Amy: And then when it goes back down-

Marcus: And when it going back down-

Amy: -it’s going to-

Marcus: it’s going back into blue pie.

Amy: Okay. That makes sense.

Marcus: And that’s blue and brown pie.

Lara: Ok, I’m going to need you to explain that in the circle. I’m not joking.

The first thing to notice in clip 4 is in the contrast to clip 3, when the students were saying they were frustrated with the movement of the idea toward pie charts. When Lara suggests, in turn 110, that they ‘forget [the pies]’ Marcus actively resists what he calls ‘disposing the pies’ (turn 113). After Lara asks how they are going to model energy in turn 108, Marcus describes how pies are exactly how they are going to model energy (turn 111).

As Marcus tells this story of the blue and brown pie he becomes very emphatic, gesturing vigorously with his hands and emphasising his meaning. Amy responds vocally to his emotional display (turn 116), and in other moments she and Kurt laugh and shake their heads at Marcus’ display. We do not try to claim that the emotion that Marcus exhibits in the telling of the brown and blue pie story is evidence of his owning the representation, but we do draw the reader’s attention to the contrast between the message in this clip compared with that in clip 3. We claim that the contrast between these moments suggests that Marcus is not simply repeating the story offered by the instructor, but is appropriating and changing the representation as he understands it. In the second half of this clip, we see the blue and brown pie representation developed across the group members, and in future clips we will observe the stability of this representation.

The story of blue and brown pie identifies forms of energy

In response to Lara’s suggestion of moving away from the pie charts, Marcus constructs a story about the energy in the ball bounce that focuses on what he calls ‘blue pie’ and ‘brown
pie’. He emphasises forms of energy by labelling ‘potential pie’ and ‘kinetic pie’ (turn 117), but quickly changes to blue (kinetic) and brown (potential) in turn 119 and 120. An important part of Marcus’ model construction here is that the pie changes colour on its fall toward the group (from brown to blue), or that energy is transformed from one and that when it hits the ground it loses some of its blue ‘pie-ness’ (turn 120), which then becomes ‘blueberry’. These two turns suggest that Marcus is using the blue (blueberry) and brown to represent different forms of energy, and the pie transforms from one form to another. When it hits the ground, the energy that was in the blue form is lost and goes everywhere even as it changes into other forms of energy. An interesting point in this exchange is that Marcus inserts his explanation of elasticity into the blue and brown pie story as the explanation for why some energy is lost into other forms (turn 121).

In the second half of the clip, after the initial story is told by Marcus, Amy and Kurt enter the discussion in turns 124–130. In this interaction, Amy and Kurt help Marcus to connect the colours blue and brown to the types of energy, kinetic and potential. Lara pushes the group to explain what these words mean (turn 131), and the brief exchange that follows shows all three students describing the blue pie as kinetic pie (turns 134–139). By turn 143, the conceptual model has become slightly more refined, with the students connecting the canonical forms of energy (potential and kinetic) to their descriptions of blue and brown pie. Finally, the idea that the pie gets ‘more blue’ as it goes down suggests energy transfer from one form to another.

From turn 146 to the end of this clip, Amy and Marcus work together to connect all the pieces of the blue and brown pie story. Toward the end, Amy takes over the story, saying that on the way back up, the pie changes back to brown (turn 152), representing potential (turn 155), which is affirmed by Marcus (turn 153, 155). Overlapping one another’s speech, Marcus and Amy build off one another’s sentences to construct the idea that at the highest point the pie is all brown pie (turns 156–165). They complete the cycle by considering when the ball is going back down and describing the pie ‘going back’ into blue pie (turn 166–169).

In the restatement of the whole blue and brown pie story, we see pieces of the idea of transformation embedded in the talk from Marcus and Amy. They use language of the pie ‘changing’ (turns 152, 153), and ‘going back to’ (turns 168, 169), suggesting the idea that the pie is transforming from blue to brown. Additionally, because the entire story was recapped in this section, we see connections between moments of the ball’s path and what the pie would look like, including being completely blue just as it hits the ground (turn 141) and being completely brown as it reaches the highest point (turn 156–165). We do not have clear evidence in this section of the student talk of where the energy goes. In other words, there is no talk of transfer in this section. It is possible that Amy’s comment in turn 148 is suggesting that when the ball hits the ground the energy is transferred out of the ball, but it is unclear from her talk and Marcus’ follow-up. Additionally, the talk about the pie changing from blue to brown pie makes it unclear whether the students see the entire pie as a single kind of energy, or portions of the pie as different kinds of energy. In other words, there is no talk of a pie that is simultaneously both blue and brown.

Development of a conceptual model

What we see happening in this set of four clips is the development of a shared conceptual model between Kurt, Amy, and Marcus. The development of the model is scaffolded through interactions with the professor and by the design of the activity, but at the end of this series of clips we see evidence that Marcus and Amy have appropriated the model as they share the ideas with Lara (the undergraduate instructor). At the end of clip 4, we have the sense that Marcus and Amy have together constructed a conceptual model about how the energy in the
system changes, and Lara warns them that they should be prepared to share this explanation in
the large group discussion.

**Day 2: The large group takes up the conceptual model**

Day 1 of the ball bounce activity ends shortly after the student groups complete the small
group ball bounce activity and are tasked with thinking about how to present their work for
the large group class meeting the following day. On day 2, the students begin the class by
developing whiteboards for the large group board meeting (approximately 30 students
gathered in a circle to present their groups’ whiteboard to one another). The process of
whiteboarding their work is a non-trivial matter for the students. Three questions that the
students are asked to answer on their whiteboard include: (1) What did you learn? (2) What
rules can you make? (3) What questions do you still have? At this point in the semester
(approximately one third of the way through the class) students are still working to understand
how best to present their work on the whiteboards.

We enter day 2 after students have created their whiteboards of the ball bounce activity
and have begun to share their findings in a large group board meeting. In the large group
discussion, the students gather for a board meeting with each group of three students holding
one representative whiteboard. The instructor remains silent, waiting for a student group to
begin presenting their work. The discussion opens with a student group explaining what they
learned about kinematic graphs and technical issues with the motion sensors. The student
group finishes and 20 s of silence follows. Finally, Ana opens up with a discussion of the
energy and what makes the ball stop.

**Clip 5: Ana presents only potential energy that is lost with each bounce**

Ana: So our group, well, our group kind of learned about…
We were kind of struggling with the idea of like how does the ball stop? We’re like...it stops.
Then after much deliberation we realised that it’s a change in energy of the ball.
Before it gets dropped it has potential energy then as you drop it when it hits the
ground it transfers energy… to the ground in the form of sound and so it loses a little
bit of energy so the next time it goes back up… it doesn’t go up as high because it
doesn’t have as much like energy.
So then the next time it goes back up, it doesn’t go up as high because it doesn’t have
as much like energy and speed as before and so then with each like bounce it loses a
little bit more energy until at the end it’s like has nothing, I guess, left and it stops
bouncing.
It doesn’t have I guess as much potential energy cause it still has some kind of energy
in the ground but we don’t really know what’s gonna happen if someone kicks it or
you step on it.

In this short clip, we see Ana articulate the difficulty her group had with determining how
the ball eventually comes to a stop. She describes the ball as having potential energy when it
is at some height and the ball transferring energy to the ground when it hits (turn 502). She
connects the transferring energy to the ground idea to the idea of the ball losing a bit of energy
each time it goes back up, until ultimately the ball has no energy left (turn 503) and it stops
bouncing. However, at the end of this clip Ana articulates a confusion she still has about the kind of energy that is left in the system after the ball stops bouncing. She asserts that it does not have as much potential energy, but she expresses uncertainty about the kind of energy that might still remain, in turn 504.

At this point, Ana’s story contains potential energy as the only energy, and while there is talk about energy being transferred Ana expresses confusion about the details of how this works. In addition to Ana’s vocalised story, we note that her group’s whiteboard had a pie chart representation (see figure 2) that showed a solid pie getting smaller each time the ball hit the ground. The representation is consistent with her story of the energy getting less each time the ball hits the ground, but the solid colour of the pie makes it clear that Ana’s model only includes potential energy.

In the clip that follows, Marta starts where Ana left off. She asks for elaboration about Ana’s group’s board by contrasting the representations she sees there (figure 2) with what she sees on another group’s board (see figure 3).

**Clip 6: Marta builds off Ana’s explanation to add kinetic energy**

505Marta: To go off what you said (gestures to Ana) and looking at that… motion map which is blue and red (gestures to Marcus’ group’s board),
506So at the top it’s full of potential energy and as it goes down it loses potential energy and gets full of kinetic energy?
507Ana: Mhmm.
508Marta: And it goes up it has, it’s going up with kinetic energy.
509Ana: Right or, or whatever potential energy it has left (shrugs). Like I kind of did the same thing in my pie charts but I didn’t put what made it go up.
510So I guess what we could define is what drives it? Is it potential energy or kinetic energy?
511Marta: Is kinetic energy pushing it that way? (motions upward)
Ana: Yeah like what, yeah what is the energy? I mean, it’s energy but you know which type of energy is the one that makes it like go up and down, I guess, or keeps it moving?

Because if it’s potential energy, this one would make sense (gestures to her group’s board) because you’re draining it of potential energy. Result is it stops moving. (gestures to Marcus’ group’s board) Unless, you’re saying kinetic energy makes it not move and that’s why it goes up more blue and then stops.

Marcus: The energy it has doesn’t make it stop move, or move

Ana: I don’t… Does anyone follow what I was saying?

(A few students mutter acknowledgement of her question.)

Ana: You know what I’m trying to say?

Student off camera: I understand I…

Ana: I don’t know if I’m, I feel like it makes sense to me, but I don’t know if it makes sense to anyone else.
In the beginning of clip 6 we see Marta draw attention to the different descriptions of the scenario provided by the boards from Marcus’ and Ana’s groups. An interesting note about this comparison is that up until this point the board from Marcus’ group has not been presented, but the structure of the board meeting is such that Marta is able to draw from not only what has been said by others, but also she sees on whiteboards in the whole classroom. With Marcus interjecting only once in this clip, Ana and Marta focus on trying to understand how the two boards are alike and different, and what the implications of these similarities are for understanding the energy story.

In making sense of the difference in the two boards, we see the focus become one of understanding the role of the forms of energy in their models. Marta draws attention to understanding the kinetic and potential energies (turn 506), and we understand from Ana’s response that her group focused primarily on potential energy (turn 509). At this point, Ana articulates a subtly different question than the one from clip 5 where she wanted to understand what made the ball stop. In turn 510, Ana asks what drives the ball upward. Marta follows up on this question, and she and Ana use words like ‘drives’, ‘pushes’, and ‘makes’ (turns 510, 511, 512), making the focus on understanding the causal agent behind the ball’s movement.

At the end of this segment, we see Ana articulate the difference between seeing the ball’s loss of potential energy as the cause of the ball stopping (turn 513) and seeing the kinetic energy as stopping the ball (turn 514). In this brief discussion, Marta and Ana are trying to understand which form of energy is the mechanism behind the ball moving upward or stopping. Ana directly appeals to Marcus to understand the role kinetic energy is playing in his description (turn 514), and Marcus responds to this query by saying it is not energy that is the mechanism behind the ball’s movement (turn 515). In response to Marcus’ dismissal, Ana appeals to the rest of the students to see if her argument is making sense, and a few students affirm her question. In the next clip, we will see Sylvia (a student from neither Marcus’ nor Ana’s group) rearticulate this question.

Clip 7: Marcus introduces transformation from potential to kinetic energy

520 Sylvia: Well I’m interested in knowing why it is you guys (gesturing to Marcus’ group) did it that way versus that way (points to Ana’s board).
521 Instructor: (whispers to Marcus) Why don’t you guys explain what you did…
522 Sylvia: …Like I feel like once it hits the ground… like I don’t know. Just explain it.
523 Marcus: Yeah, well, basically the height that you have when you’re gonna release the ball, it’s at that point you have your potential energy. It’s the only energy you have potential, and as you release the ball it gains kinetic energy, gets faster. And because it’s reducing its height from ground your, you have less potential energy.
524 So basically, you have one standard amount of energy from the time you have the ball in your hand, which is fully potential. And as it falls, the potential decreases because the height is less and the kinetic increases as it gains speed, velocity, going down. So there’s gonna… as you go down you have more and more kinetic energy, and less and less potential energy.
525 When it hits the floor you have, the split second before it hits the floor it’s all kinetic. When it hits the floor you lose energy due to sound, elasticity of the ball, heat, all the other components of energy… dissipation, whatever.
Then you have all kinetic coming, so then you have, coming off the ground it’s all again fully kinetic but you have less energy because of energy dissipated due to the impact. And then as you go up it comes, you have less and less kinetic more and more potential until it reaches its maximum height. Which will be less than the previous maximum height because of the energy lost.

But again you have 100% of your energy being potential and then you basically just repeat with each bounce—where you’re fully potential at the top and then you get increasingly more kinetic going down, and impact-time comes back again. Basically it repeats itself in that motion. I don’t know if that explained everything?

Sylvia: Yeah, I get it.

Marcus: You get it?

Ana: We’re both saying the same thing.

Sylvia: Yeah.

Marcus: (shakes his head side to side)

Ana: We’re not even thinking about kinetic energy really.

Sylvia: ...Ok that’s why it’s…

Ana: The way he explains it, yeah, if it’s the same amount of ener… like the change of energy, like the purpose between potential and kinetic are the same being dropped. It’s just every time you have less energy cause you dissipate energy to the ground.

Sylvia: So its just only changing the potential.

Ana: Yeah.

Sylvia: (points to Marcus’ board) And that’s put together…kinetic, potential.

This clip is dominated by Marcus explaining his reasoning about the forms of energy (potential and kinetic) to the larger group. However, this interaction begins with Sylvia drawing a comparison between the whiteboard from Ana’s group and the board from Marcus’ group. She articulates her primary question to be around the decision to include the kinetic energy (turn 521). Prompted by the instructor, Marcus enters the dialogue where he explains the specific model developed by his small group.

In Marcus’ explanation, we see him start by moving through the physical picture of the ball falling. He says that at the beginning the ball has all potential energy, which gets smaller as the ball falls (turn 524). At the same time, Marcus says the ball is gaining kinetic energy because it is getting faster. He pauses at this point and clarifies that there is only one amount of energy and that energy is either potential or kinetic energy (turn 525). Marcus also emphasises that as potential energy goes down, kinetic goes up, allowing for the sum of the total energy to remain the same. He then goes through the process of the ball hitting the ground and what happens at the point of contact. Marcus finishes his explanation by highlighting that the entire process repeats again, ending by asking if he explained everything (turn 528).

Sylvia, who initiated this interaction, indicates that she is still confused about the differences between Ana’s and Marcus’ boards (turn 529, 531). Ana interjects (turn 532) and says that they are doing the same thing, but Ana’s group does not talk about kinetic energy. Instead, she explains that her board is capturing only the idea that energy is lost when it makes contact with the floor (turn 538), and Sylvia restates that the difference between the two boards is only that Marcus has both kinetic and potential and Ana only has potential.
The conceptual model develops in the large group discussion

In this series of clips from day 2, a question arises in the board meeting conversation about the purpose of these forms of energy. Ana and Marta start by articulating a question about the form of energy which is the mechanism behind the ball in clip 6. The discussion between potential energy being drained from the ball versus the kinetic energy stopping the ball arises from Ana, Sylvia, and Marta drawing comparisons between the presentations of Ana’s and Marcus’ whiteboards, and the question of what stops the ball’s movement is a result of comparing the forms of energy on the two whiteboards. It appears that Ana’s group has focused primarily on the decrease of the energy over time, and less on which form the energy is in. On the other hand, we saw in clip 4 that Marcus, Amy, and Kurt had concentrated mainly on how the energy changed from one form to another. In bringing these two descriptions together and contrasting them, the students were able to make progress in deciding that the forms of energy are not distinctly different while, at the same time, allowing that the total amount of energy decreasing accounts for the ball not bouncing as high.

We argue that the large group discussion has extended the conceptual model we articulated in Marcus’ group in clip 4 to the large group. We also note that many of the elements of MI came into play to support this conceptual model development and appropriation through the use of the representations of the pie charts on the whiteboards, the whiteboards themselves as artifacts of the consensus reached by the small group, and the instructor moves which encouraged student ownership and responsibility for the discussion. We are not arguing that the presence of any of these elements caused the productive model building to occur, but in understanding how this event unfolded, we want to draw attention to the role the MI elements played in shaping the event.

Discussion

In this paper we set out to describe the ways by which the two elements of MI interact in the unfolding of an event in the classroom. While we believe that the sequence of clips 1 through 7 demonstrates how these elements interact, we do not mean to imply that the sequence represents excellent teaching or learning. Instead, we intended to portray a sequence of events that represent the ways in which a focus on the MTS can combine with the MTI to encourage student participation in the development of a conceptual model. In this section, we intend to examine some of the subtle messages that analysing these clips uncovered.

How is it that clip 7 came to be?

Clip 7 represents the culmination of the conceptual model being shared with the large classroom group. In our description of a conceptual model, we emphasised how these models are developed in the discourse, and thereby focused our analysis on the elements that were shared amongst the class.

In the beginning of day 2 we drew the reader’s attention to the whiteboards the students had created. The whiteboards play a key role in the development of consensus in the small groups and in allowing small groups to share their findings with the rest of the class. In clip 7 we see this play out in a way that is distinct from perspective that the whiteboards are simply an artifact of student talk. Sylvia starts by comparing the boards of two individual student groups. One of these groups (Ana’s) had shared their findings prior to Sylvia’s question, while the other had not. We see the pedagogical tool of whiteboards being leveraged to help bring the conceptual model developed by the Marcus’ group to the discussion with the large
group. Furthermore, the instructor plays an important role in clip 7 by prompting Marcus to explain his whiteboard. In doing so, the instructor opens the floor to the students in Marcus’ group, both encouraging them to share their findings with the large group and implicitly signalling to the rest of the classroom that what Marcus is about to share is of importance. We see the instructor using the work done by the small group in helping the large group make progress conceptually.

Additionally, we notice the difference in the amount of talk from the instructor in the day 1 clips as compared to the day 2 clips. The instructor is far more involved in the small group discussions than in the large group. In this way, the instructor is able to guide the conceptual model building while still allowing students to grapple with their own ideas and participate in the model building process. In MI and learning as participation, we do not mean to imply that the instructor does no work in guiding the development of models, but instead that the work that s/he does is not focused on the delivery of information.

The role of the instructor in MI

In the clips representing day 1 of this sequence, we see a distinct difference in the ways the two instructors in the classroom interact with the students. The senior instructor, the professor, interacts with the students in clips 1 and 2 in a way that communicates that he is trying to lead them in a particular direction. His goal is to introduce them to pie charts, and he purposefully guides the conversation in the direction that helps the students see how a pie chart could be useful. In direct contrast to that is Lara, the junior instructor, who encourages the students to follow their own thinking, even going so far as to say in clip 4, ‘Forget the pies. Because the pies don’t make sense to you at this point.’ In contrasting these two instructors, we see the tension between strict guidance of ideas and following student-generated ideas playing out in their interactions with the small group.

It is not entirely clear that both roles are necessary, but it is true in this sequence of clips that both roles were present. We are not sure what would have happened without these two different kinds of interaction. We suspect that it is in part Lara’s dismissal of the pie charts that encourages Marcus to tell the story of the brown and blue pie. When the professor is present, the students spend their time trying to figure out the point he was trying to make with the pie charts, and when he leaves, they move to a discussion of how ridiculous the representation was from their perspective. However, when Lara moves to entertain the absurdity of the representation, the students rebel and push back. It may have been the contrast between these two roles that allowed the students to take ownership of the pie chart representation and flesh out the idea.

Even so, we do not mean to imply that the enactment of MI requires the presence of two separate instructors. Indeed, it seems possible that a single instructor could play both roles at different times through the discourse. Instead, we mean to draw attention to the tension that may exist in the MI classroom between strict guidance and the individual development of student ideas, and point out that in an MI classroom there is at times room for both kinds of interactions. This tension represents one possible place of further investigation in future work.

What is the curriculum?

A key to understanding how the three elements of MI interact in the classroom is reconceptualizing what we mean when we say the MI curriculum. As discussed throughout this sequence, the materials that the students interact with are only a small part of the instructional design. As we have moved through discussing Days 1 and 2, we have leaned heavily on the
other elements of MI to understand the unfolding of the event. The goals of the lesson, which are often communicated through the instructor guide, are important to understanding the instructor’s push toward the pie chart representation. The instructor knowledge of the MTS and of the goal of having students participating in the building of the scientific conceptual models is important for understanding why he does not intervene when students are having trouble making sense of the ball stopping in the large group discussion. Finally, the pedagogical content knowledge (Shulman 1987) that the question of why the ball does not bounce as high will elicit the idea of energy contributed to the writing of the student materials and the questions the instructor uses. In instructional design, folks tend to think of curriculum as being simply a collection of the written worksheets with which students interact. It is our hope that in unpacking the ways the key elements of MI interact to contribute to the unfolding of this event for the students that we have problematized this idea of curriculum. Instead, we hope that individuals interested in the MI curriculum consider a deep understanding of the modelling cycle and the MTI as essential pieces of the curriculum.

Conclusions

An important part of the goals of MI has been to engage students in the practice of doing physics. This practice of doing physics aligns the participactionist perspective that learning involves the ongoing transformation of participation. Thus, as students are engaged in doing physics they are learning. We believe that an essential part of doing physics is developing and validating scientific conceptual models. When we examine the practice of students in the second half of the paper, we see students doing exactly this. We observe a small student group engaged in the process of negotiating the use and meaning of a representation that could help them understand the particular phenomenon in question. Then we observed students comparing two specific models developed by two different groups. In the board meeting the discussion leads to a consensus about the purpose of the different forms of energy. This conclusion is essential to the process of developing a basic model that includes the law of energy conservation. As students move through this process of developing specific models of phenomena and extending them to basic models agreed upon by the community of physicists, they are engaging in the process of doing physics. The focus on models and model building encourages students to develop a deep understanding of what is important in physics, which is larger than either the concepts understood or the problem-solving skills developed.

We contend that a coherently developed and model-centric curriculum, pedagogy, and approach to learning promote participation in the practice of doing physics. MI for university physics is one such example. We have undertaken an analysis of classroom events to illustrate the process of students engaged in the complex process of model building. In MI, the instructor assumes the role of a physics expert and uses this expertise to select classroom activities, monitor and guide discourse, and promote student participation in the practice of physics. We encourage instructors and researchers interested in reproducing positive results seen from the MI learning environment to consider the key elements of MI (modelling cycle, and the MTI) as important to successfully enacting a curriculum centred on the practice of doing physics. In doing so, we hope to see further exploration on issues such as the role of the instructor in this kind of learning environment, and the ways students learn the norms of the classroom. We do not attempt to claim MI is the sole environment where these types of doing physics take place, but we do contend that this paper has demonstrated the deep disciplinary practices of the MI environment.
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