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Analysis of a physics teacher's pedagogical 'micro-actions' that support 17-year-olds' learning of free body diagrams via a modelling approach

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ABSTRACT
Great teaching is characterised by the specific actions a teacher takes in the classroom to bring about learning. In the context of model-based teaching (MBT), teachers' difficulty in working with students' models that are not scientifically consistent is troubling. To address this problem, the aim of this study is to identify the pedagogical micro-actions to support the development of scientific models and modelling skills during the evaluation and modification stages of MBT. Taking the perspective of pedagogical content knowing (PCKg), it identifies these micro-actions as an in-situ, dynamic transformation of knowledges of content, pedagogy, student and environment context. Through a case study approach, a lesson conducted by an experienced high-school physics teacher was examined. Audio and video recordings of the lesson contributed to the data sources. Taking a grounded approach in the analysis, eight pedagogical micro-actions enacted by the teacher were identified, namely 'clarification', 'evaluation', 'explanation', 'modification', 'exploration', 'referencing conventions', 'focusing' and 'meta-representing'. These micro-actions support students' learning related to the conceptual, cognitive, discursive and epistemological aspects of modelling. From the micro-actions, we identify the aspects of knowledges of PCKg that teachers need in order to competently select and enact these micro-actions. The in-situ and dynamic transformation of these knowledges implies that professional development should also be situated in the context in which these micro-actions are meaningful.

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Introduction

It is widely recognised that the hallmark of great teaching is the instructional actions taken by a teacher during classroom teaching (OECD, 2005). These actions include ways of monitoring and assessing students' learning, and facilitating their learning (Galton, 2000; Tan, Liu, & Low, 2017). In the context of physics teaching and learning, this implies that the effectiveness of a pedagogical approach is dependent on the specific actions that teachers take to develop students' scientific understanding and skills. We

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see evidence of this in model-based teaching (MBT), a pedagogical approach that has recently gained popularity among physics educators. MBT is a pedagogical approach that engages students in generating, evaluating and modifying models, just like the way scientists build models in theory building. Models are abstractions of objects, processes or events (of the physical world) that capture key structural, behavioural or functional features significant to understanding their interactions (Hubber & Tytler, 2013; Nersessian, 2008). Examples of models in physics include mathematical models (e.g. $F = ma$, $\text{emf} = -d\varphi/dt$), pictorial models (e.g. free body diagrams (FBDs), field diagrams, wave diagrams), gestural models (e.g. Fleming's Left Hand Rule) and textual models (e.g. Newton's laws of motion). In developing scientific models, scientists need to construct and validate them, which Gilbert and Justi (2016) refer to as modelling.

The popularity of employing MBT for physics teaching and learning is partly triggered by a focus on models and modelling in the science curricula of various countries (e.g. Australian Curriculum, Assessment and Reporting Authority's (2015) *The Australian Senior Secondary Curriculum (Physics)*; Ministry of Education's (2016) *Physics Singapore-Cambridge General Certificate of Education Advanced Level Higher 2 2018*; National Research Council's (2012) *Next Generation Science Standards*). Reports (e.g. Campbell, Zhang, & Neilson, 2011; Hansen, Barnett, Makinster, & Keating, 2004; Saari & Viiri, 2003) of students' improvement in achievement scores after undergoing MBT further fuelled educators' support for this teaching approach. The evaluation and modification stages of MBT are seen to promote formative assessment, and hence learning. In constructing a model, students select the attributes of the phenomenon to be represented in their model that they perceive as plausible to achieving the intended objective (Lehrer & Schauble, 2003). Engagement in this abstraction process makes their thinking and reasoning behind the attributes of the models visible to others (Ainsworth, Prain, & Tytler, 2011), thus allowing teachers to work on these ideas with the students.

Despite its popularity and potential for deep learning to take place in MBT classrooms, studies that look more closely into what teachers did during MBT found that its implementation remains patchy, particularly in the evaluation and modification stages. Khan (2011), on studying teachers' enactment of MBT, reported low occurrences of teachers' evaluation and refinement of students' constructed models during MBT. Teachers in Waldrip and Prain's (2013) study found guiding students in understanding the nature of representations and progressing from self-generated to scientific ones challenging, despite training and researchers' assistance. Such difficulties were not merely reported by novice teachers, but by experienced teachers as well (Hubber, 2013). These observations are particularly worrying as a meta-review by Coe, Aloisi, Higgins, and Major (2014) reveals that excellent content knowledge and an understanding of the purposes of the pedagogical approach are not sufficient to enact a pedagogical approach effectively. Rather, teachers need to know what specific actions to take, as well as 'how, when and why', to enhance students' learning (Caena, 2011). These studies suggest that effective implementation of MBT cannot be achieved by merely following prescribed stages of generate–evaluate–modify. Rather, the MBT teacher needs to constantly make decisions on 'how' and 'when' to enact a particular action, which is dependent on one's ability to rationalise 'why' a particular action is able to achieve an intended outcome of learning. In order to address the difficulties teachers experience with the evaluation and modification, this study aims to identify the pedagogical actions taken when working with students'

models during the evaluation and modification stages of MBT. We focus on these two stages in consideration of the importance of developing students' understanding of models and modelling, and the challenges teachers face in working on students' produced models. We do this by examining what a high-school physics teacher who was experienced with MBT did during the evaluation and modification stages. As teachers' actions are mainly captured in the teacher-students discourses, we draw reference from Sinclair and Coulthard's (1975) classroom discourse model, and focus the level of analysis at the most micro level of talk, that is, 'act' – a specific action taken to serve a particular learning purpose. To reflect this micro level of analysis, henceforth, we refer to these teacher's actions as pedagogical micro-actions.

Pedagogical content knowing for MBT approaches

Effective implementation of MBT requires teachers to make knowledgeable, intentional and reflective instructional decisions in the classroom, at the opportune time to bring about learning, manifested as pedagogical micro-actions. According to Lund, Metzler, and Gurvitch (2008), this entails a transformation of the knowledges of pedagogy, content, students and environmental context, and the transformed knowledge is commonly referred to as pedagogical content knowledge (PCK; Shulman, 1986). However, Cochran-Smith (2006) argues that the transformation of these knowledges is not a static one, as the notion of PCK might seem to imply. Rather, the micro-actions teachers take during the evaluation and modification stages of MBT are the result of dynamic sense-making of these knowledges 'on the go' as teachers receive real-time information about students' thinking and reasoning of their models and consider the environmental context (e.g. time, curriculum focus, exam focus) they are in against the backdrop of content and pedagogical knowledges they possess. To capture this ongoing and active transformation of knowledges, we take on the constructivist notion of pedagogical content knowing (PCKg) (Cochran-Smith, 2006) instead of the more conventional but static concept of PCK (Shulman, 1986) as our theoretical perspective in this study. In the following sub-sections, we present a review of the literature on the various aspects of PCKg in relation to MBT: what it entails, the content knowledge in respect to modelling, and the challenges students face in generating models and those teachers face in supporting students in evaluating and refining their models, and discuss what a constructivist perspective might imply to the conduct of this study.

The MBT pedagogy and what it involves

MBT generally refers to approaches whereby learners are engaged in the exploration of a phenomenon, construction and reconstruction of models in the light of the results of scientific investigations and evidences (Campbell, Oh, & Neilson, 2012). Models can come in various forms – physical, mathematical, pictorial and textual. MBT approaches have been found to enhance students' conceptual understanding (Hubber, Tytler, & Haslam, 2010) and awareness of the forms and functions of representations used in scientific models, such as the use of arrows in FBDs (Prain & Tytler, 2012), can engage students in higher-order thinking processes such as analysing, inductive reasoning and evaluating (Sins, Savelsbergh, & van Joolingen, 2005). While we can trace the emergence of MBT

approaches to cognitive-historical research on mental models as a way of learning (e.g. Khan, 2011), modelling is also regarded as a key scientific practice that students need to develop if the goal of science education is to enculturate learners into the practices of science (National Research Council, 2012).

MBT approaches generally include three key processes of modelling of the scientists in their knowledge-building work: generation, evaluation and refinement (Clement & Rea-Ramirez, 2008; Khan, 2007, 2011). More specifically, MBT entails students creating models; using their models to make predictions, test or generate scientific explanations about different processes and communicate their findings and ideas; evaluating their models through comparison to empirical data and to an expert's scientific model or to their peers; and revising their models to reflect changes in their thinking brought about by new evidences generated through investigations or examples being presented. These activities necessarily entail four dimensions of modelling: epistemological, conceptual, cognitive and discursive (Vo, Forbes, Zangori, & Schwarz, 2015).

Guided by an investigative question, models are constructed to serve a particular purpose of inquiry into a phenomenon. This is consistent with the *epistemic* consideration – the 'how' and 'why' – that scientists take into account when evaluating how well the models they create serve as scientific tools (Schwarz et al., 2009; Vo et al., 2015). In creating the models, key features or attributes of the phenomenon need to be identified, and their relationship specified (Romberg, Carpenter, & Kwako, 2005). Scientific concepts are also used to support the construction of their models (Johnston, 2008). All these point towards the importance of *conceptual* knowledge in modelling.

The purpose of modelling is to use the model to produce explanations for observed phenomenon. Such *cognitive* work involves testing the models through investigations, observations and inferences as students connect emerging evidences and explanations to their constructed models. Such cognitive work is evident in Windschitl, Thompson, and Braaten's (2008) MBT approach, which involves students developing a tentative model or hypothesis about a causal or associative relationship in the phenomenon, making systematic observations to test these hypotheses, creating models that account for the observations, evaluation of the model against standards of usefulness, predictive power or explanatory adequacy, and revision of the model and application to new situations. At the same time, in creating models, students make use of different forms of representations to present their ideas and use them to argue for the claims they make, which entails the need for students to understand the *discursive* practices of modelling. In other words, while MBT may consist of the three stages of constructing, evaluating and refinement of models, the act of modelling involves conceptual, cognitive, discursive and epistemological knowledge. These four aspects of knowledge signal the need for an expanded view of subject-matter content in modelling beyond the specific science concepts (conceptual), and to include subject matter-specific reasoning and thinking with the models (cognitive), forms of representations and patterns of argumentation (discursive), as well as understanding the functions of models (epistemological).

Constructing models: FBDs

Models are important tools that help scientists and students solve problems (Kindfield, 1999; Kohl, Rosengrant, & Finkelstein, 2007; Kozma, 2003; Rosengrant, van Heuvelen,

& Etkina, 2009). FBDs, the focal model in this study, are a pictorial representation that is commonly taught to students in physics to think and reason about forces acting on a body. The focus of an FBD is on the object of interest and on the forces exerted on it by other objects (Rosengrant et al., 2009). Its construction requires all four aspects of modelling. *Conceptually*, FBDs are linked to Newton's laws, which describe the relationship between a body and the forces acting upon it, and its motion in response to those forces. Its purpose (*epistemological*) is to identify all the forces acting on a body so that the resultant or its components can be thought about, and subsequently related, to its motion. As a *discursive* (representational) practice, the most common scheme used in the local curriculum – among the many ways of drawing FBDs – is the system schema. It represents the object of interest pictorially (usually with a rectangle), and arrows (vectors) are used to represent the direction and magnitude of forces of other objects acting on it, whether in direct contact or at a distance. By representing the forces acting on an object vectorially, it allows one to visualise how the abstract forces are acting on the object, and hence employ vector manipulation to derive resultants and components of the forces (*cognitive*). To further illustrate these four aspects of producing FBDs, we will use the context of tug-of-war examined in this paper as an example. Figure 1(A) shows two people tugging the ends of a rope, without any lateral movement. The FBD of each person is shown in Figure 1(B), whereby each rectangle represents one person, and the arrows represent the forces acting on each person by other bodies (i.e. the

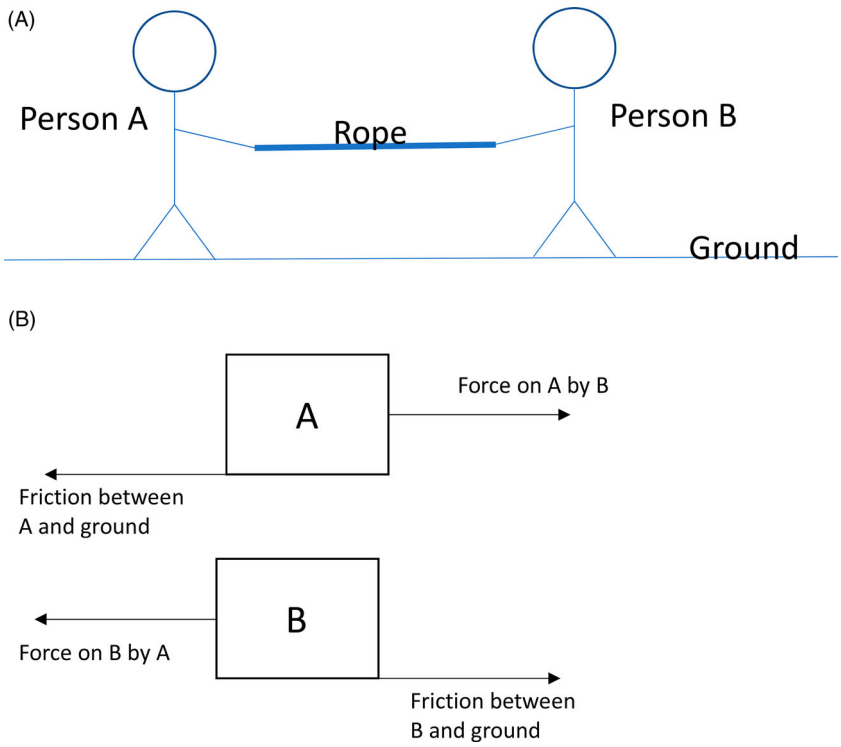


Figure 1. Illustration of FBDs as a representation of a tug-of-war phenomenon. (A) Tug-of-war. (B) FBDs of a tug-of-war phenomenon.

other person and the ground). The two arrows on each body of equal length signify that the forces acting on each body are equal, producing a resultant force on each body to be zero. This representation is coherent with Newton's First Law, which states that a body at rest would have a resultant force of zero.

Challenges students face in modelling and with constructing FBDs

Producing models like FBDs is often a key instructional objective in science classrooms. Studies (e.g. Kohl et al., 2007; Rosengrant et al., 2009) have found a positive correlation between students who drew force diagrams correctly and the ability to solve problem successfully. Similarly, Kindfield (1999) found that experts in genetics make extensive use of diagrams to think about the problem during problem-solving. Kozma (2003) also found that it is instinctive for chemists to generate models to reason about experiments. However, despite its importance to problem-solving and emphasis in instruction, students find modelling challenging (Sins et al., 2005). In relation to constructing FBDs, studies show that students have difficulties in many aspects of modelling. In the discursive aspect, students found it difficult to distinguish the use of arrows for representing different forces (real, resultant and components) (Kondratyev & Sperry, 1994), often naming them incorrectly (Aviani, Erceg, & Mesic, 2015). Cognitively, they have difficulty in applying vector manipulation to derive resultants or components (Knight, 1995). Nguyen and Meltzer (2003) explain that it could be due to their weak understanding of vectors. Conceptually, misconceptions of Newton's laws are reflected in the FBDs that students produced (Aviani et al., 2015). Furthermore, studies by Rosengrant et al. (2009) and Heckler (2010) show that students often produce FBDs without understanding the purpose of this resource in helping them solve problems in dynamics. These studies show that, like scientists who need to go through iterative cycles of refinement of their models before they are accepted, students' models need to be assessed and refined so as to achieve coherence with the evidences obtained and the set of scientific knowledge that has been widely accepted. In other words, evaluation and modification of models are essential stages of MBT if deep understanding of scientific knowledge, development of scientific thinking and discourse, and an understanding of the epistemological practices in the advancement of science are to be achieved.

Teachers' role in facilitating learning in an MBT environment

The range of competencies students need to develop in order to produce scientific models and the challenges that students face with the practice of modelling imply the importance of the teacher's role in MBT. Yet, studies show that teachers face challenges in facilitating learning in an MBT environment despite being experts in the content or having undergone training in MBT. Prain and Tytler (2012) reported that teachers were found to have trouble coping with non-standard student models because they might be unsure about how to conduct the assessment process. Considering that these teachers were experts in the content knowledge of their own disciplines, this difficulty signals the need for an expanded view of what encompasses subject-matter knowledge in MBT. In our review of MBT in the previous section, this meant that the notion of subject-matter knowledge in MBT needed to be expanded to include cognitive, discursive and epistemological aspects, besides the more

conventional conceptual knowledge. In another study by Waldrip and Prain (2013), they highlighted teachers' difficulty in facilitating group discussions of different student arguments and justifications when dealing with students' models. This suggests that general pedagogical skills like questioning might need to be contextualised to the pedagogical environment that emphasises on modelling. Given the constructivist standpoint taken on PCK in this study, and the fact that evaluation and modification of students' models can only be enacted with the knowledge of students' models and their reasoning, a teacher's pedagogical action has to be a dynamic transformation of the knowledges of content, pedagogy and students in relation to the context in which MBT is implemented. By context, it highlights the influence that the social, cultural, political and physical environment has in affecting pedagogical decisions made in the classroom. This aspect is evident in Yeo, Tan, & Lee (2012) recount of a teacher's 'lethal mutation' (p. 48) of problem-based learning (PBL) as he regarded time to be lacking and certain skills and knowledges highlighted in PBL to be tangential to the national examination curriculum. In other words, the pedagogical micro-actions taken by teachers are always a construction in relation to the knowledges of content, pedagogy, student characteristics (their specific understanding in this case) as well as the social, cultural, political and physical environment rather than a retrieval of the knowledges already existing in one's mind.

To capture this dynamic transformation of knowledges into pedagogical actions, it is not sufficient to examine lesson plans or the broader pedagogical moves such as the triadic moves (Initiate–Response–Evaluate/Follow-up) (Lemke, 1990) taken by a teacher. Rather, the perspective of PCKg, as well as what we know about what great teaching entails, suggests the need to uncover in fine-grained details the 'how, when and why' of pedagogical decisions taken during an MBT lesson. In this study, we focus on the evaluation and refinement stages of MBT as studies suggest that these two stages are the weakest link in MBT implementation. The integrative nature of the four components of PCKg implies the need to study actions in-situ. We aim to identify the micro-actions taken by a teacher in facilitating students' evaluation and modification of their models so as to guide students towards more scientifically consistent ones. As discourse is the most common mode in facilitating learning, our analysis focused on classroom discourse between the teacher and students. According to Sinclair and Coulthard (1975), classroom discourse can be analysed at different levels of granularity – lesson, transaction, exchange, move and act. As effective teaching is reflected by the specific instructional actions taken by a teacher as they work on students' ideas, capturing this would require us to focus our analysis on the finest-grain size of the discourse structure. We refer to the acts of the teacher as pedagogical micro-actions. Thus, our aim of this study is to investigate the pedagogical micro-actions taken by an experienced teacher during the evaluation and modification stages of a modelling lesson in physics, or more specifically, in the construction of FBDs. These pedagogical micro-actions are the specific acts performed by a teacher on a turn-by-turn basis in the classroom. To this end, we seek to find out:

(1) What pedagogical micro-actions were used by the teacher during the assessment and refinement phases of MBT?
(2) What aspects of the students' models and modelling practices were addressed during the assessment and refinement phases of MBT?

Methodology

This study employed an exploratory case study approach (Yin, 2003) to address the research questions since the pedagogical micro-actions of a teacher during the evaluation and modification stages of MBT were not well understood. Consistently with our constructivist stance, we take on Merriam's (1998) pragmatic approach to constructivist inquiry to ensure that the research process is manageable, rigorous, credible and applicable. We chose one case example so that an in-depth analysis can be performed to give us insights to the types of micro-actions needed to guide students towards constructing scientifically consistent models. Our case was thus selected based on the aim of the study and what it could reveal about the phenomenon examined with the following criteria: (1) the presence of social interaction, such as dialogue between students and teacher; (2) the successful achievement of learning outcomes; and (3) an experienced teacher in MBT. The limitations of using only a single case are that comparisons of the micro-actions between different teachers cannot be made, and the results of this study cannot be generalised. Nonetheless, a constructivist inquiry provides structures aimed at generating inductive reasoning and interpretation – in this case, a grounded approach. The result is a rich description of the case that will help readers identify the instances where they could find similarities with their own situation.

Context

The study was conducted at a local junior college (the equivalent of a high school) in Singapore. A junior college offers a two-year pre-university programme that prepares students for the General Cambridge Examination (GCE) 'A' Level. About 28% (based on data from 2009 to 2014) of students admitted to elementary schools progress to junior colleges (Ministry of Education, 2015). Admission to a junior college is based on their qualification obtained at the national examination (GCE 'O' Levels) taken at Grade 10. Computed based on a formula that yields a range of 6–54 points (6 being the best score) from the GCE 'O' Levels results, a junior college admits students with 21 points and below. This junior college admits students who score 13 points and below, which is around the median score of the population among all the junior colleges.

The case study involved Ms T, an experienced teacher who had taught physics for eight years in the school. She had been applying MBT in the Ignite Programme for two-and-a-half years. The Ignite Programme is an initiative of the school to develop critical thinkers and future-oriented leaders through seminar-style pedagogy that encourages exploration, reflection and expression of ideas. Admission into this programme is by application, and selection is based on academic results and interviews. Ms T had learnt about MBT from a workshop she attended at the U.S. Since then, she had worked with the second author of this paper to revise the instructional strategies in MBT to adapt to the needs of her students and the local physics curriculum.

The students observed in this study were from Ms T's Grade 11 (16–17 year-olds) class. They were in the Ignite Programme. The class of 32 students was made up of students of different races and nationalities around the South East Asia region, which is typical of a multi-racial, multi-national country, even though Singaporean Chinese made up the majority of the students in this class. Nonetheless, the students in this class had attended

the local secondary schools (Grades 7–10), and were proficient with spoken and written English, the working language used in this country.

Participation in this study was voluntary and participants were allowed to leave the study any time during the research process. Ethics clearance was obtained from the Nanyang Technological University (IRB-2013-12-040) as well as the local ministry of education. Written consents from the school leader as well as participants and their parents (for students below 21 years old) were obtained. Efforts were taken to ensure participants' anonymity, such as limiting specific details about the school and using pseudonyms that would not divulge the identities of the participants in journal and conference papers.

Description of the modelling activity

The MBT lesson examined in this study was centred around Newton's Third Law of Motion. The related learning objectives included students being able to draw FBDs for connected bodies to represent the forces acting on the bodies in the phenomena, identify pairs of action and reaction forces in phenomena, state their relationship, and make inferences about the effects of these forces on an object. As FBDs are pictorial models used for thinking about forces acting on a body, modelling is thus both a learning outcome to achieve as well as a means to achieve the learning objectives. In this activity, students were tasked to produce FBDs to represent the forces acting on the bodies of a tug-of-war phenomenon to account for the motion observed.

This model-based activity was part of a series of three modelling activities that focused on Newton's laws of motion. Previous modelling activities had focused on Newton's First and Second Laws. From those activities, students had already learnt to draw FBDs for single bodies (i.e. unconnected bodies or interacting bodies), including the form, function and conventions of an FBD prior to the modelling activity in this study. However, this was the students' first attempt at representing FBDs for complex systems.

This case study is taken from a single lesson of 1.5 h. It was selected based on discussion and successful revisions of students' models that are aligned with the conceptual, cognitive, discursive and epistemological dimensions of modelling. In fact, one of the students was able to 'successfully' refine his initial FBD to make it more aligned to scientific conventions and with the phenomenon. In this context, 'successfully' also meant that the students' models answered the initial task requirement more appropriately.

The modelling activity took place during the latter part of the lesson; the first part of the lesson was used to go through a worksheet previously given. It started off with the class watching a demonstration of two stationary students engaged in a tug-of-war, with force sensors connected to them to measure the forces they were exerting on each other (refer to Figure 2).

Data from the force sensors were recorded by a data logger, which showed equal forces registered by each force sensor at any one time. The teacher then led the class to interpret the data registered on graphs (refer to Figure 3). Students were then instructed to draw FBDs to explain the motion of each of the two students.

Table 1 shows a summary of the sequence of events that took place during the 1.5-h lesson.

Figure 4 illustrates an example of the acceptable model, which is made up of two individual FBDs showing the forces acting on each of the bodies.

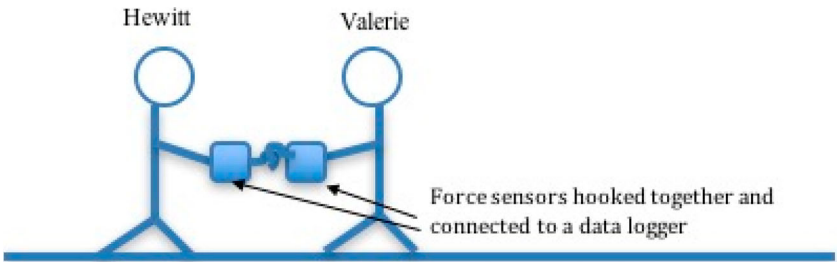


Figure 2. Set up of tug-of-war phenomenon.

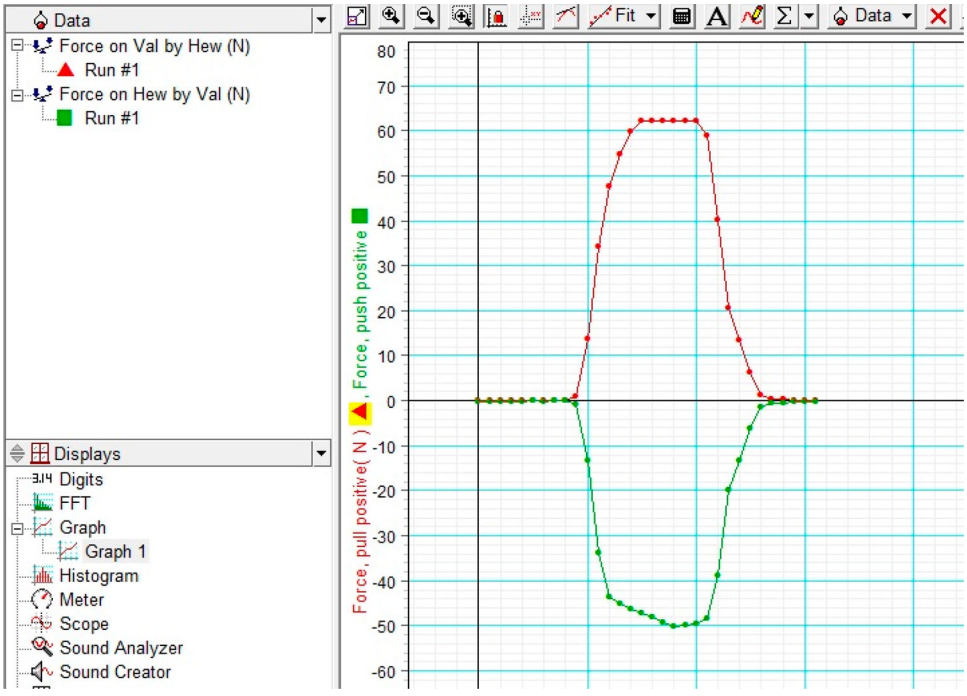


Figure 3. Graphs generated by the force sensors in the tug-of-war phenomenon.

Table 1. Lesson outline.

50 min	Recap of previous lesson's objectives (Newton's first and second laws), followed by going through answers to homework assigned in previous lesson.
40 min	Newton's 3rd law modelling activity facilitated by the teacher (this is the part of lesson examined in this study) (1) Enactment of a tug of war phenomenon with two students connected to force sensors pulling each other: a data logger registered the forces exerted by each student on the other and data was displayed as a graph of force against time. (2) Class discussion of data, facilitated by teacher. (3) Assignment of task whereby teacher instructed students to construct FBDs to represent the phenomenon and the data collected. Time was given for students to construct the FBDs individually. The teacher walked around and observed the students' FBDs. (4) Selecting and calling upon three students to present their FBDs on the board in front of the class. (5) Class discussion of three FBDs, each one in turn although reference was made to other FBDs to highlight similarities or differences among them.

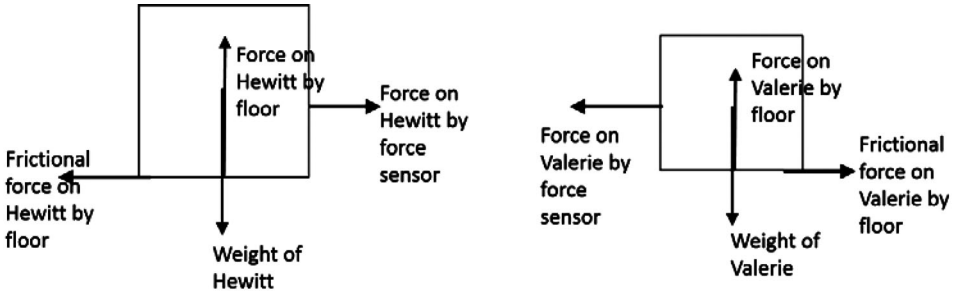


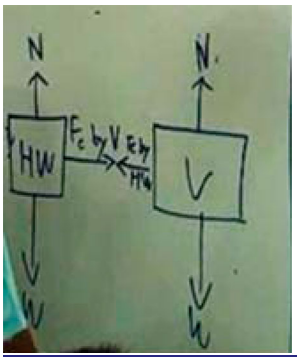
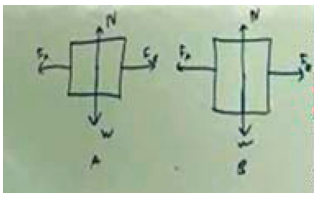
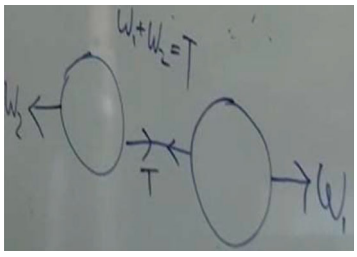
Figure 4. Example of acceptable FBDs for observed tug-of-war phenomenon.

Two models (Zachary's and Samuel's) were selected for reproduction on the whiteboard in front of the class because of their representativeness of the models constructed by the students, while a third model was subsequently proposed by Frank during the early part of the evaluation of the two models (refer to Table 2). The teacher then guided the class in engaging in a public negotiation of each student's model, starting with Zachary's, then Samuel's and Frank's in sequence. This is where the case study is based upon.

Data sources

The lesson observed was recorded using video cameras and audio recorders. The camera was situated at the back of the classroom to ensure that it was not intrusive of the lesson. In addition, an audio recorder was fastened around the teacher to ensure that words spoken by the teacher were captured clearly. During the whole class discussion, the video camera was mostly directed at whoever was presenting (e.g. teacher or student presenter). The video and audio data were transcribed following the conventions of Jewitt, Kress, Ogborn, and Tsatsarelis (2001), which included all the verbal productions and multimodal micro-actions enacted by both the teacher and her students. All these were done to ensure that much of the experiences in the classroom was captured.

Table 2. FBDs selected for discussion, and reasons for their selection.

		
Student 1: Zachary	Student 2: Samuel	Student 3: Frank
This model was chosen mainly because friction was missing on each of the FBDs and hence did not show coherence to the natural phenomenon.	This model was mainly chosen because it lacked clarity and did not adhere to convention as friction was not drawn at its point of application.	This model was chosen because the student had joined the FBDs of the 2 people involved instead of drawing individual FBDs of each person.

Data analysis: a grounded approach

A grounded approach was used to identify the pedagogical micro-actions of the teacher and their functions. Only the evaluation and modification stages of students' models were examined. To ensure rigour and credibility of findings, the analysis of the data, conducted by the first author and discussed with the second author, was systematised and involved the following:

(1) Reading the transcripts of the classroom discourse once through to obtain an initial sensing of the data.
(2) Defining a series of categories that could describe and interpret what took place during the class discussion. These inductive categories were based on the function of the teacher's micro-actions, which emerged after the data had been read many times until no new categories was identified, rather than being determined prior to the observation of the data. As the categories were not defined from the start, one challenge was to determine the classification of micro-actions, in particular if the micro-action did not appear frequently. We resolved such issues by constant reference back to the data to ensure consistency in the definition of each category. The other challenge was to determine if a micro-action was essential or not. The determination of an essential micro-action is guided by the components of the PCKg framework; that is, it is a pedagogical act that relates to the targeted content and students' ideas enacted in the specific context of evaluation and modification stages of MBT. An example of an essential micro-action can be seen in Excerpt 1, Turn 362. Here, the question 'why do you show them connected like that' when referring to the two bodies drawn connected to each other in the FBD was to seek the student's thinking about the FBD he drew with respect to the phenomenon observed. A non-essential micro-action, on the other hand, does not relate to the components of PCKg, in particular the content or students' ideas. An example is a remark such as 'ok hold on ah'. The list of categories was then used in the analysis of the data to test for its robustness, with new categories being identified and redefined when needed. This is a cyclical procedure midway between coding and analysis (Glaser, 1992). Having established the categories, the class-based discourse was re-examined and coded. The coding and interpretation of the data were then triangulated with the second author. Any differences in categories and coding were negotiated until a common agreement was reached. Due to a single case study, these categories were not applied to other topics. Hence, the transferability of the categories was not determined at this point of writing. This could, however, be an opportunity for further research.
(3) A frequency count of each micro-action was made to have a sense of the prominence of each micro-action.

Findings

Eight pedagogical micro-actions were identified from the evaluation and modification stages of MBT that addressed the issues students had in creating a scientific model for the 'tug-of-war' phenomenon they had witnessed. Table 3 lists the eight pedagogical micro-actions, issues addressed, frequency of occurrences, dimensions of modelling competencies, purposes and example of excerpts where the micro-actions are demonstrated.

Table 3. List of pedagogical micro-actions identified, issues addressed, frequency of occurrences, dimensions of modeling competencies, purpose and example excerpts.

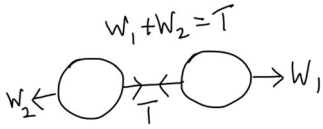
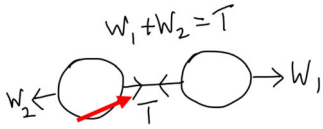
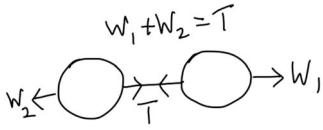
Type of pedagogical micro-actions	Frequency	Issues addressed	Frequency	Dimensions of modelling competencies	Specific areas addressed	Excerpts
Clarification	21	Clarify task requirement	3	Epistemological	To develop an understanding that modelling is purpose- and context- driven.	Excerpt 1
		Clarify meaning of representations used	18	Conceptual Discursive	To understand the meaning imbued onto the model To understand the link between the representations in the model and students' mental model	
Evaluation	14	Evaluate adequacy of models	2	Epistemological	To develop an understanding that modelling is purpose- and context-driven	Excerpt 2
		Evaluate completeness of representations	3	Conceptual	To develop an awareness of the representativeness of the model to the phenomenon	
		Evaluate coherence of models with scientific principles	3	Conceptual	To elicit evaluation of the consistency of the models with scientific principles	
		Evaluate adherence to conventions	4	Discursive	To elicit evaluation of the conventions of specific models (e.g., FBD)	
Explanation	12	Provide/seek justification (teacher or students)	6	Conceptual	To find out students' conceptual understanding of the phenomenon and the scientific principles used	Excerpt 3
		Modify models for greater clarity, coherence and adherence to scientific convention	6	Cognitive	To test out capability of models to generate inferences (conceptual relationships)	
Modification	12	Explore alternative ideas In-depth examination of phenomenon	7	Cognitive	To direct revision of models to reflect changes in thinking brought about through new evidences generated through investigations	Excerpts 4 & 5
		Make explicit reference to or recalling scientific conventions associated with scientific model	3	Discursive	To request for modification of models to adhere to conventions	
		Direct attention to specific features or parts of students' models	2			
Exploration	10	Discuss the purpose of representations (presence or absence) in the model	5	Cognitive	To evaluate models through comparison with empirical data and to experts' models or peers'	Excerpts 6, 7 & 8
		Clarify task requirement	5	Conceptual	To examine the phenomenon in greater details	
Referencing conventions	4	Clarify meaning of representations used	4	Discursive	To identify the representation system of science	Excerpt 8
Focusing	3	Evaluate adequacy of models	3	Discursive	To direct attention	Excerpt 5
Meta-representation	1	Evaluate completeness of representations	1	Epistemological	To develop meta-representational capabilities whereby the purpose(s) of representations in a model are discussed	Excerpt 8

These eight micro-actions (refer to Table 3) were identified from the class discussion the teacher had as she addressed Zachary's, Samuel's and Frank's models in sequence. It was also observed that the teacher usually started with clarification and then requested for explanations, after which she performed the modification micro-action. Exploration occurs with modification. Referencing conventions were observed to occur at any time whereas focusing usually took place with clarification or explanation. The following sub-sections will describe and illustrate these micro-actions with excerpts taken from the class discussion.

Clarification

'Clarification' was the most frequent micro-action observed, particularly in clarifying meanings imbued in the representations used. This occurred 18 out of 21 clarification micro-actions observed, which relates to the conceptual and discursive aspects of modelling.

Excerpt 1

Turn	Speaker	Utterance	*Multimodal representation	Micro-action
part of 360	Teacher	Ok now, can we take a look at Frank's diagram? Yes? Yes Frank, can you explain to us what's your W; weight?	Pointing to 'W_2' on the free body diagram of Frank 	Clarification
361	Frank	Er, I don't know. A force, it's a force and represented by W.		
362	Teacher	Why do you show them connected like that?	Pointing to the connected arrow between the two circles 	Explanation
363	Frank	Because they are connected		
364	Teacher	Ok. So would you say that this is a free body diagram of Hewitt and this is a free body diagram of Valerie?	Points to circle on the left then circle on the right 	Clarification
365	Frank	Yes. Actually you can just separate it		

Two examples of this micro-action are illustrated in Excerpt 1. The model produced by Frank (refer to the figure in Turn 360) was different from the ideal model shown in Figure 3 in two key areas. First, the labelling symbols (W_1 and W_2) did not seem consistent with the conventional use of symbols for labelling forces in physics. The symbol W is typically used to label the weight of an object, by convention. Second, the model showing two circles connected with a line labelled

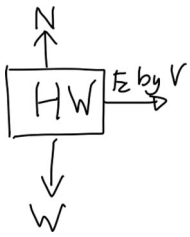
T differed from the individual circles used to represent each body in the ideal model. It is thus not clear how Frank defined the system in his FBD – the two bodies as individual systems or one system. Thus, the teacher's question in Turn 364 sought to clarify this point. The response from Frank suggests that his intent and the externalised model were not coherent. In other words, the role of the clarification micro-action in this instance addresses the conceptual and discursive aspects of modelling so as to ensure that the meanings intended by the student in his model are made explicit to the teacher and his peers to reduce the chances of misinterpretation. This is particularly important in images and abstract symbols (e.g. *W*) as they are open to various interpretations (Kress & van Leeuwen, 2006).

Another issue addressed in clarification micro-actions, though less frequent, is that of task requirement, which somewhat relates to the epistemological function of modelling. This micro-action is observed when students showed confusion over the purpose of the modelling. An example shows the teacher reminding a student that the task is to draw FBDs of the students at tug-of-war rather than that of the force sensor connected to the students, although the teacher could perhaps extend this clarification micro-action to discuss why the FBD of the force sensors would not necessary address the problem at hand.

Evaluation

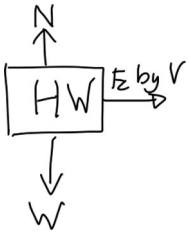
The 'evaluation' micro-action refers to the teacher assessing or facilitating peer assessment of students' models. This is the second most frequent of all types of micro-actions observed (14 times). The areas assessed are 'adherence to conventions', 'coherence', 'completeness' and 'adequacy', whereby the frequencies of their enactments were almost similar, though 'adherence to conventions' had the highest frequency count (4 out of 14) among the four areas. These areas are related to the cognitive, discursive and conceptual aspects of modelling. Excerpt 2 exemplifies some of the evaluation micro-actions as the teacher directed her students to evaluate the conceptual, cognitive and discursive aspects of modelling.

Excerpt 2

Turn	Speaker	Utterance	Multimodal representation	Micro-action
302	Teacher	Oh looking at this one diagram now. Ok don't see this part here.	Points to free body diagram of Hewitt	Focusing
		Looking at this diagram alone, does it show that the resultant force is equal to zero?		Evaluation
303	Student	No		

(*Continued*)

Excerpt 2 Continued.

Turn	Speaker	Utterance	Multimodal representation	Micro-action
304	Teacher	No. There is this one here right?	Points to the force pointing to the right on the free body diagram of Hewitt	
		So where you think, is there, should there, has he represented all the forces acting on Hewitt?		Evaluation
305	Students	No		
306	Teacher	What could there be? What else could there be? Sorry, William you were saying?		Exploration
307	William	Force he exerted		
308	Teacher	Force he exerts ah. Ok uh, so ok, William is saying that we should on the free body diagram also show the force that Hewitt exerts. What do you all think?		Evaluation

This model (refer to Turn 302) evaluated is created by Zachary. Comparing his FBD to the ideal one, the missing arrow (frictional force) acting to the left of the body meant that there would be a resultant force to the right, implying that the body would move to the right. This is contrary to the evidence showing that the bodies were stationary during the tug-of-war demonstration. Hence, the excerpt shows Ms T eliciting an evaluation of the reasoning (cognitive) involved in the construction of the FBD.

While Turn 302 elicited an evaluation of the coherence of the model to the evidence (stationary bodies) obtained from the phenomenon, in Turn 304, Ms T sought an evaluation of the 'completeness' of the model by asking if 'he represented all the forces on Hewitt'. This led to William's suggestion (Turn 307) to include the 'force he (Hewitt) exerted'. This created the opportunity for Ms T to address the discursive practice of drawing an FBD as she tossed the response back to the class and asked them, 'What do you all think?' (Turn 308). Since an FBD only represents the forces acting on a body, rather than by the body, this question essentially sought an evaluation of the adherence to conventions.

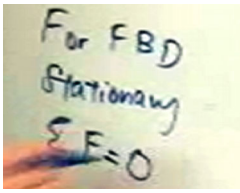
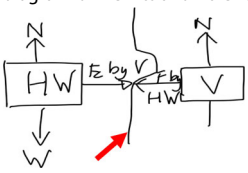
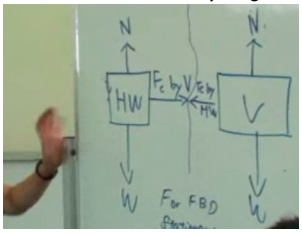
In addition to what is illustrated above, there were two occurrences of evaluation for adequacy to task requirement. Referring to the model drawn by William, which showed the FBD as one connected body, Ms T prompted the students to assess whether the model satisfied the task of explaining the motion of the two bodies in the tug-of-war. This micro-action addresses the epistemological aspect of modelling.

Explanation

The 'explanation' micro-action was used to provide or seek justifications about the model constructed. Seven occurrences showed the teacher providing the explanation, while the rest were the teacher's requests for the students to provide explanations. Five of the 12 'explanation' micro-actions were related specifically to the conceptual relationship

between the body's motion and the forces acting on the body. Two examples of the teacher eliciting an explanation from students are shown in Excerpt 1, Turn 362, and Excerpt 3, Turn 294. In Excerpt 1, Ms T's question was to find out Frank's thinking behind his depiction of two connected bodies in his FBD. His response gave us an insight into the conceptual framework on which his model was based.

Excerpt 3

Turn	Speaker	Utterance	Multimodal move	Micro-action
292	Teacher	Ok, if I look at the FBD, right since they were stationary, you are saying that resultant force equals to zero.	Writes down on board 	Explanation
		So we look at Zachary's case, does it show the horizontal forces? He has drawn, he has drawn them separately.	Draws a middle line to separate the free body diagram of Hewitt and Valerie 	
		Let's just look at Hewitt ok. Ok, let's just look at Hewitt itself.	Points to Hewitt's free body diagram 	Focusing
		Now, does it show that Hewitt is stationary? Just by looking at this free body diagram.		Evaluation
293	Students	No		
294	Teacher	Why not?		Explanation
295	Andrew	Because there's a resultant force		
296	Teacher	There's a resultant force where?		Clarification
297	Andrew	To the right		

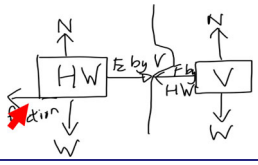
In Excerpt 3, the need to seek an explanation arose when students merely gave a simple 'No' as a response to her close-ended question – whether the 'resultant force is equal to zero', as inferred from the model drawn. Her elicitation for an explanation in this case was to seek an extension of their simple response so that their reasoning could be made clear. The result of making the thinking clear to the teacher, in both cases, made it possible for Ms T to probe their thinking further and, as a result, extend their reasoning. In the first case, Ms T was able to prompt an evaluation of whether the model was aligned to the task (Excerpt 1, Turn 364). In the latter case (Excerpt 3, Turn 296), Ms T prompted for an elaboration of Andrew's response as she sought to find out the direction of the resultant force acting on the body.

Modification

The 'modification' micro-action was used mainly to prompt for revision of students' models to achieve greater clarity and coherence. This micro-action occurred 12 times throughout the discussion of models that addressed the cognitive and discursive aspects of modelling.

An illustration of this micro-action to improve the coherence of students' model with the evidences can be seen in Excerpt 4, which is related to Frank's model. As mentioned earlier, his FBD had a missing force, which would result in an inference that was contrary to the observed motion of the two students in the demonstration. Ms T's question about whether 'we have friction in this direction' suggested to the class that there should be a frictional force in the FBD. Phrased as a question, it was an invitation for the students to also consider the necessity of friction in the FBD.

Excerpt 4

Turn	Speaker	Utterance	Multimodal move	Micro-action
330	Teacher	Do we have this? Do we have friction in this direction?	Draws friction to the left on FBD for Hewitt	Evaluation
		If not how can you account?		Modification

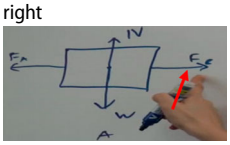
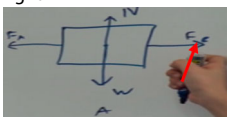
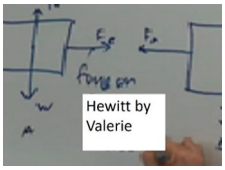
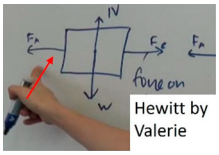
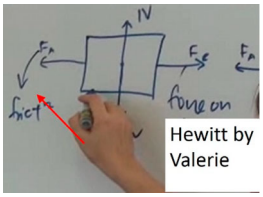
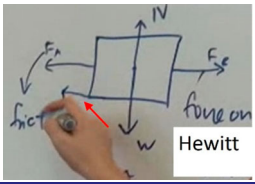
While the above illustration of the modification micro-action showed the teacher making the modification, Excerpt 5 shows how the teacher facilitated the refinement of Samuel's model.

In this case, the arrow representing frictional force (labelled F_c in Turn 346) was not at the appropriate location of the model. By asking students to propose where to 'present friction', the teacher was requesting students to modify the original position of friction represented by the leftward arrow labelled F_A (see Turn 348 for the diagram). The result is a model that was more aligned with the conventions of FBDs, which relates to the discursive practices of modelling.

Exploration

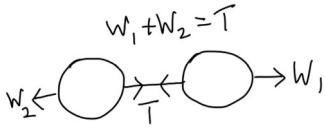
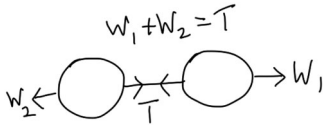
The 'exploration' micro-action is for the discussion of alternative ideas proposed by students or through deeper investigation of the phenomenon. Out of a total of 10 'exploration' micro-actions, 5 focused on exploring alternative systems. An example is seen in Excerpt 6, where Frank had represented the two connected bodies as one system. To assess students' knowledge of the conventions of FBDs (discursive aspects of modelling), the teacher challenged the class to consider if tension represented by the arrows between the two circles and labelled '*T*' should be included in this model (Turn 374). From Turn 375, we can infer that the student was aware that tension was considered an internal force for this system. Even Frank disagreed that internal forces should be represented in an FBD,

Excerpt 5

Turn	Speaker	Utterance	Multimodal move	Micro-action
346	Teacher	Samuel has drawn 2 *(horizontal)* forces. Ok, can you explain to us again what is this force here? What were you thinking then?	Points to the force F_B that points to the right 	Clarification
347	Samuel	By Valerie		
348	Teacher	This is by Valerie?	Points to the force F_B that points to the right 	Clarification
		Ok so this is the force on Hewitt by Valerie also	Writes down "force on Hewitt by Valerie" on the whiteboard 	Modification
		And what is this force?	Points to the force F_A that points to the left 	Clarification
349	Samuel	Suppose to be friction		
350	Teacher	Ok so he says is supposed to be friction. Ok so where would you present friction now?		Modification
351	Samuel	Below		
352	Teacher	Ok below here. So if now, if you say this is friction,	Writes down friction for F_A 	Modification
		ok hold on ah, we come to Frank's diagram ah,		
		ok you should also draw it at the bottom, at ground, the point at which the force is at, right Ok yes Frank?	Draws friction to the left at the bottom of the box 	

as seen in Turn 377, after the teacher got students to recall the conventions of FBDs (Turn 376). Exploring alternative systems, in this case, allowed the conceptual and discursive aspects of modelling to be addressed.

Excerpt 6

Turn	Speaker	Utterance	Multimodal move	Micro-action
374	Teacher	But can you treat them as one? You want to treat them as one whole thing?	Pointing to the connected arrow between the 2 circles 	Exploration
		If you treat them as one whole thing, should you represent these forces here? If you treat them as one object. This is something to think about right?		Evaluation
375	Student	Internal forces		
376	Teacher	Ya. Do you represent internal forces on the free body diagram? If you treat them as one.	Pointing to the whole diagram 	Referencing conventions
377	Frank	No.		

Apart from the discussion of alternative ideas, 'exploration' also involves prompting the students to examine the phenomenon in greater details, as seen in Excerpt 7. In Turn 318, the teacher prompted students to think deeper about the interactions that Hewitt had with the surrounding objects apart from his interaction with Valerie. By having students explore the phenomenon deeper, she was essentially addressing the conceptual aspect of modelling.

Excerpt 7

Turn	Speaker	Utterance	Micro-action
318	Teacher	Have you all considered all the interactions that Hewitt has with the object that surrounds him besides Valerie? What else, what other interactions does Hewitt have? Besides his weight and normal, what else is present?	Exploration
319	Students	Friction	

Referencing conventions, focusing and meta-representations

The 'referencing conventions', 'focusing' and 'meta-representations' micro-actions were observed to be less common as compared to the other micro-actions discussed above. The 'referencing conventions' and the 'focusing' micro-actions are related to the discursive aspect of modelling, while the 'meta-representations' micro-actions relate to the epistemological aspect.

'Referencing conventions' has to do with making explicit reference to the conventions associated with the scientific model, such as the general rules of drawing FBDs. This micro-action was observed when the teacher wanted to remind students of the general conventions of drawing FBDs before she got them to evaluate whether the conventions were adhered to in their own models. Such a micro-action highlights the FBD as an institutionalised language (use of representation), whereby its use is constrained by a set of rules that the scientific community has agreed upon.

The function of 'focusing' is to intentionally direct students' attention to specific features or parts of students' models. We observed this when Ms T pointed to specific parts of the FBD while she was making reference to certain features of the models in her verbal talk. This is perhaps a necessary pedagogical micro-action when discussing models since images are open to various interpretations (Kress & van Leeuwen, 2006).

Meta-representation refers to thinking about the representations used in a model (diSessa, 2004), which includes their purposes in particular contexts, how they support the function of the task, and critiquing and comparing their suitability for the tasks. Hence, the function of 'meta-representing' in this study is to elicit students' thinking about how entities are represented (or not represented). In this sense, it relates to the epistemological aspect of modelling. It was the least frequently used micro-action by the teacher and it occurred only once during the assessment and refinement phases of students' models. Excerpt 8, Turn 286, provides an illustration of this micro-action.

Excerpt 8

Turn	Speaker	Utterance	Micro-action
286	Teacher	… back to Dom's question first.	
		You say, is it necessary to draw the … ok the normal and the weight on the object right?	
		I ask for the free body diagram.	
		Free body diagram, the usual convention is the, all the forces acting on the object right?	Referencing convention
		But sometimes we simplify things ok by ignoring them because in this case, what can you say about them?	Meta-representing

In Turn 286, the teacher was prompting the students to think about the need to represent the normal and the weight of the object in the FBD. As she mentioned in that turn, all the forces acting on an object have to be represented in an FBD by convention. However, it is common to leave out forces that are not significant to the problem in an FBD. In this case, the vertical forces (normal and weight) play no part in the horizontal motion of the body. By questioning students about the necessity to draw these forces in the FBD (Turn 286) despite convention, she was essentially getting her students to relate the act of modelling and their purposes.

Discussion

The findings of this study identify eight pedagogical micro-actions taken by a teacher in addressing the challenges her students faced with producing scientifically consistent

models. Through these micro-actions, students were guided to think about the purposes of model construction, the conventions used in constructing FBDs and the coherence of their constructed model with scientific knowledge and the observed phenomenon. The enactment of these pedagogical micro-actions demonstrates the in-situ process and dynamic transformation of knowledges. We draw two key inferences from the findings: (1) the specific knowledges in terms of the components of PCKg that are crucial for effective implementation of MBT; and (2) the professional development that could enhance teachers' competencies to enact these pedagogical micro-actions.

Pedagogical micro-actions: an in-situ process, a dynamic transformation of knowledges

The enactment of the pedagogical micro-actions demonstrates the situated and dynamic nature of teacher knowledge, learning and teaching. Set in the context of the evaluation and modification stages of MBT, whereby students' thinking and reasoning were sought in real time, these micro-actions cannot be pre-determined or scripted. Taking Excerpt 5 as an example, the micro-action of 'modification' (Turn 350) was a follow-up of Samuel's response to Ms T's request for an 'explanation' (Turns 346 and 348) to find out the meaning inscribed in Samuel's labels of forces in the FBD. Given that Samuel's response in Turn 349 was constructed in real time, Ms T's follow-up question cannot be scripted in advance. Rather, it has to be constructed at the point in time of responding to Samuel's reply. Similarly, Ms T's request for an 'explanation' in Turn 346 can only be constructed when Samuel's FBD was produced and presented to her. In other words, given the interactive nature of the evaluation and modification stages of MBT, these pedagogical micro-actions reflect the constructivist view of knowledge, and demonstrate how these micro-actions have to develop in accordance with the responses students give in real time. This implies that these pedagogical micro-actions cannot be pre-planned. Rather, teachers will have to react and construct these micro-actions in accordance to students' responses.

The pedagogical micro-actions also show that there is always a dynamic transformation of different knowledges – content, pedagogy, student and environment. For each micro-action, we can identify these four knowledges in play. For example, in Turn 350 in Excerpt 5, the micro-action of 'modification' reflects the knowledges of: content (i.e. conventions of drawing force along its line of action), pedagogy (i.e. questioning to prompt thinking), student (i.e. understanding the meaning that Samuel had inscribed in the arrow labelled F_x) and environment (i.e. knowledge of the syllabus focus and requirements). The decision of taking a particular micro-action must also necessarily be a selection among competing aspects of each type of knowledge. For example, in Excerpt 1, there are many aspects of the FBD (content) that a teacher could select for evaluation, such as the conventions of FBD (e.g. shape of body, the labels), conceptual coherence (e.g. how forces W_1, W_2 and T are related) and purpose of the modelling task. In deciding what aspect of the model to address, Ms T would have to select among these different aspects of the content. In deciding how to go about addressing the FBD, she would also need to decide on the sequence of addressing the issues. In this case, she had sought to seek clarification of the labelling of the forces before seeking an explanation for the FBD to be drawn 'connected like that' and evaluation of whether they had satisfied the

task requirements (Turn 364). The use of questions to facilitate the evaluation of the student's model is also a selection among other possible evaluation strategies such as an authoritative assessment by the teacher. Similarly, decisions had to be made in relation to which aspect of students' knowledge to take up, and what aspects of the environment (e.g. time, students' attitudes, curriculum needs) to consider in deciding the next micro-action. In other words, the pedagogical micro-actions are constant negotiations of the components of PCKg wherein teacher capacities are developed and mobilised by means of interactions with students, contexts, teaching tools and materials and relationships among them in a specific context (Engestrom, 1999). This implies the need for flexibility and adaptability to the conditions of the context in order to monitor, steer and adopt appropriate micro-actions according to the pre-requisites, objectives and learning processes to bring about effective learning (Bransford, Brown, & Cocking, 2000; Hatano & Oura, 2003; Vogt & Rogalla, 2009). Such in-situ and dynamic transformation of knowledges in the enactment of pedagogical micro-actions demands personal judgement, holistic schema of the teaching plan, and tacit knowledge, which could perhaps explain why MBT teachers found it challenging to identify and enact appropriate micro-actions to work on students' models (Hubber, 2013; Waldrip & Prain, 2013), and hence tend to shun the evaluation and modification stages of MBT (Khan, 2011).

Components of PCKg needed in the enactment of pedagogical micro-actions

The enactment of the pedagogical micro-actions identified in this study further informs us of the components of PCKg that teachers should possess in order to make appropriate decisions of the pedagogical micro-actions to take.

Knowledge about content

Excellent content knowledge is one of the strong predictors of good teaching (Coe et al., 2014). Yet, what counts as content knowledge is often left to one's own interpretation. Traditionally, content is often used to refer to conceptual knowledge, which, in this case example, would refer to the understanding of Newton's laws. However, Ms T's pedagogical micro-actions went beyond addressing Newton's laws (Excerpt 2), and included the cognitive, discursive and epistemological aspects of modelling too, as we see in the micro-actions in Excerpts 1 and 6 – the discursive (in Turns 360 and 376), cognitive (Turn 362) and epistemological (Turn 364) aspects as Ms T sought clarification and explanation about the way in which Frank labelled and represented the forces, and explored the plausibility of Frank's model as an alternative one (Turn 374). The different aspects of models and modelling addressed in Ms T's pedagogical micro-actions indicate what counts as content knowledge that teachers should have in order to carry out MBT competently. The four dimensions of model and modelling can thus help to define the aspects of the content that teachers should be expected to possess or develop during professional development.

Knowledge about MBT pedagogy

Caena (2011) maintains that knowing 'when' and 'why' a particular micro-action is taken is as important as knowing the micro-action. A closer examination of the pedagogical

micro-actions suggests that they perform different purposes in the evaluation and modification stages of MBT. We identify three pedagogical purposes.

The 'clarification' and 'explanation' micro-actions serve the purpose of exploring students' thinking behind the different aspects of their models (e.g. the clarification micro-action in Excerpt 1, Turn 360) and to make visible the reasoning for the constructed models (e.g. the explanation micro-action in Excerpt 1, Turn 362). The pedagogical purpose of 'evaluation', 'modification' and 'exploration' micro-actions, on the other hand, is primarily used to work on the students' ideas with the aim of progressing them towards more scientifically consistent models. An illustration of this is shown in Excerpt 2 where the question of 'does it show that the resultant force is equal to zero' elicited an evaluation and subsequently a modification of the FBD drawn. These two pedagogical purposes of *exploring* and *working-on* resemble the first two phases of Mortimer and Scott's (2003) teaching sequence of 'discuss – work-on – review'. In deciding the terminology to name the pedagogical purpose of 'exploring', we have chosen to follow Mortimer and Scott's terminology to avoid potential confusion between the same word used to name the pedagogical micro-action and purpose. The two phases 'discuss – work-on' were also espoused in the formative assessment literature, whereby Black and Wiliam (2009) emphasised the need to establish 'where students are right now' (their current state of understanding) before decisions on 'how to get there' (the intended scientific understanding) can be made. Such teaching sequence was observed in many parts of the transcript.

Between the two purposes, Ms T seemed to enact more 'discussion' than 'working on' micro-actions, as indicated by the higher frequency in the sum of micro-actions taken in the 'discuss' group compared to that of 'work-on' group. This might be necessary since a teacher has to fully understanding the students' thinking before taking appropriate actions to address their difficulties. Considering that teachers tend to have problems with working-on students' ideas despite having a clear understanding of students' thinking as reported in literature (e.g. Ruiz-Primo & Furtak, 2006), the illustration of micro-actions identified for working-on students' ideas would help to address this challenge.

We see the micro-actions of 'referencing conventions, focusing and meta-representations' as *meta-actions* taken to bring attention to the key aspects of modelling. For example, the gesture of pointing at the arrows in Turn 362, Excerpt 1, focused students' attention to the specific representation of the model so that the purpose of the model could be thought about. In Excerpt 8, the explicit mention of the conventions of constructing FBDs prompted students to think about the need to include 'normal and the weight of the object' in the FBD. These forces were auxiliary ideas that would not affect scientific coherence whether or not they were drawn in. Hence, these actions provoked deeper thought into the rules of constructing FBDs. To reflect this level of thought brought about by these micro-actions, we refer to them as *meta-actions*. These micro-actions serve the pedagogical purpose of eliciting a meta-level of thinking about the models, which, in our case study, was mainly related to the representational system of FBDs. Such awareness and thinking about representations at the meta-level is important in modelling as representations are tools with which knowledge is constructed (Kozma & Russell, 2005). Yet, our findings show that it has the lowest frequency among the three groups of micro-actions. This could perhaps reflect teachers' unawareness or difficulty in discussing representations at this meta-level, as explained by Waldrip and Prain (2013). The pedagogical functions of the micro-actions and their sequence of enactment

could provide some guidelines to teachers as to 'when' a particular micro-action should be taken at a particular point in time.

Knowledge of students

In the context of MBT, knowledge of students includes students' difficulties with models and modelling. As the pedagogical micro-actions identified in this study were carried out in relation to students' often-not-acceptable models, which concurs with existing research about students' models (e.g. Kozma & Russell, 2005; Sins et al., 2005), they indicate the challenges students experience with models and modelling.

In the conceptual dimension, modelling competencies include the ability to abstract from the features of a phenomenon. This difficulty is demonstrated in Excerpt 2 whereby students missed out on some of the forces which affected the coherence of the FBD with the evidence of the phenomenon. This can perhaps be explained by Kozma and Russell's (2005) observation that students tend to focus on surface features of the phenomenon and neglect discussing things that were occurring at the molecular or inferred level. The teacher's evaluation micro-action thus prompted students to consider the interactions the object has with its surroundings so that the forces acting on the object can be identified. Another aspect of the conceptual dimension pertains to the concepts and principles behind a model. As exemplified in Excerpt 2, students may not necessarily draw upon the appropriate scientific concepts or principles in their construction of models, unlike scientists or experts who engage in substantial conceptual talk about their models. In such an instance, an evaluation micro-action directs students in assessing the coherence of their models to relevant scientific principles.

The cognitive dimension of modelling has to do with the thinking and reasoning processes in modelling. One of the problem areas of the students' models is with ensuring the coherence of their models with the observed phenomenon (refer to Excerpt 3). This problem indicates a possibility that students do not assess the coherence and adequacy of their models with the observed phenomenon on their own, as compared to scientists who consistently test their models against evidences or perform further investigations to test their models. The explanation micro-action, as demonstrated in Excerpt 3, is thus needed to find out students' thinking in their construction of models as well as to extend their thinking in moving towards a more scientifically consistent explanation. Such cognitive processes of modelling need to be supported by the teacher, and its high frequency of enactment suggests its importance.

In the discursive dimension, the findings show that students often do not make use of conventions or representations that are consistent with that of science, a finding similar with those by Prain and Tytler (2012). All language system, including that of science, has its own conventions and rules. As such, one of the competencies in developing scientific models is to acquire the same language system of science so as to aid communication. The clarification micro-actions are thus needed to find out the meanings inscribed in the representations used by the students so that subsequent evaluation and modification micro-actions can be enacted to guide students towards a scientifically consistent construction of FBD.

In the epistemological dimension, students need to understand that modelling is purpose driven (Gilbert, Boulter, & Rutherford, 2000), and hence there need not be only one 'correct' model for any particular phenomenon. Rather, different models can

be created for the same phenomenon. Thus, the appropriateness of a model depends on the function for which the model is to serve. By enacting the evaluation micro-action to elicit students' assessment of the adequacy of models for the task required, the teacher could bring across this epistemological function of the various models.

While the challenges related to modelling might be uncovered by previous studies, the pedagogical micro-actions demonstrated by Ms T suggest that knowledge of students can only be produced in real-time interaction with the students. While there are challenges identified through previous studies or even through experiences, teachers should not make assumptions of students' ideas from the models they produce. Rather, the micro-actions provide the means in which knowledge of students can be obtained, and subsequently worked on.

Knowledge about environmental context

This study also indicates the importance of the social and political context of the learning environment in a teacher's decision on what pedagogical micro-actions to take. This study was conducted in a context where a high-stakes examination is of high priority. The physics curriculum was focused mainly in the conceptual and cognitive aspects of science, whereby students would be tested on their comprehension and application of scientific concepts and principles. These factors can be said to have contributed to the teacher's micro-actions to be largely directed at the conceptual, cognitive and, to some extent, the discursive aspects of modelling, rather than the epistemological aspect. This could perhaps explain the observation of particularly high incidences of conceptual and cognitive aspects of modelling being addressed in this study.

Implication of the pedagogical micro-actions to teacher professional development

We have demonstrated that these pedagogical micro-actions are active constructions of content, pedagogical, students and contextual knowledge, and discussed what aspects of knowledge teachers might need to make meaningful decisions of the micro-actions to take. In light that these micro-actions are in-situ and dynamic transformations of the four aspects of knowledges, professional development in MBT cannot consist only of standalone workshops that focus on the acquisition of these knowledges. Rather, the importance of developing flexible and adaptable dispositions in deciding on 'how, when, and why' a particular pedagogical micro-action is taken amidst a complex and uncertain learning environment implies the need for professional development that involve the examination, discussion and questioning of one's practices in situations of uncertainty, unpredictability, swift change and complexity (Caena, 2011). Such situations can only be found in a real classroom where learning is taking place. Taking a leaf out of the lesson study approach (Takahashi & McDougal, 2016), developing one's pedagogical micro-action thus entails the critical analysis of one's practice in a real classroom in understanding and evaluating the 'how, when, and why' in the enactment of micro-actions, and the effects on students' learning. In this way, teachers are continually challenged to construct their knowledge about the types of micro-actions, when they should be enacted, and the purposes in the context in which these micro-actions are meaningful. As well, such situational learning also takes into consideration the socio-cultural and historical

context in which learning and the micro-actions are conducted. The constant negotiations among the stakeholders, the actors and the context ensure meaningful micro-actions that serve the purposes of the environment in which MBT is implemented.

Conclusion

This study was aimed at addressing teachers' difficulties in working with models produced by students during the evaluation and modification stages of MBT. The eight pedagogical micro-actions, their purposes and sequence of teaching yielded from this study provide an insight into what, how, when and why teachers could do when supporting students in developing competencies in producing scientifically consistent models. While these micro-actions are identified through a single case study, our goal is not to provide a comprehensive list of micro-actions. Future studies can include more cases to find out more of such micro-actions and their effectiveness in developing scientific literacy. Rather, the constructivist perspective of PCKg reminds us that these pedagogical micro-actions are always situated and transformative. Hence, we hope that the findings of this study have provided insights into the 'how, when and why' of these micro-actions, which in turn can provide the grounding for the micro-actions taken. Beyond the context of MBT, pedagogical micro-actions are reminders of what great teaching is.

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