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Teacher Enaction: Modeling How Teachers Build New Mechanism Concepts in Students' Minds

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Abstract: Science teaching requires enabling students to form, and build on, new mechanism concepts, in association with standardised formal terms in the textbook. These dynamic concepts are taught by the teacher through a combination of moves, including narratives, gestures, diagrams, and evaluative procedures such as questions and exams. Students' mechanism concepts are generated and refined as a result of this enactive process, along with the association of these concepts with formal terminology. The formal terms allow later activation of specific parts of the mechanism. The cognitive processes underlying this extended building, where detailed and componential mechanism concepts are created in other minds, are not known. We present a preliminary account of this process, based on an analysis of teacher-student interactions. This account adapts constructs from two enactive cognition models – embodied simulation of language, and embodied simulation of others' mental states.

Keywords: Teacher enaction, mechanism learning, embodied simulation theory of mind, embodied simulation theory of language

1. Introduction

Science learning involves internalising mechanism concepts that students have not previously encountered (such as transpiration and mitosis). As learning advances, students are required to progressively build on, and manipulate, these mechanisms. Many of these concepts are based on imperceptible constructs (such as guard cells), whose activity and state changes are central to the new mechanisms that are introduced. Textbook descriptions capture these imperceptible constructs, and their state changes, in specific formal terms, generating a standardised academic language that the student needs to internalise to practice science. Students in an average classroom mostly have access to only these formal terms and some diagrams, through their textbook. The practice of science teachers focuses on helping students adapt their sensorimotor experiences, in ways that ground these terms, figures and activity states, and thus help students understand, and manipulate, the mechanisms.

Let us now see what actually happens during the process of photosynthesis. The following events occur during this process:
(i) Absorption of light energy by chlorophyll.
(ii) Conversion of light energy to chemical energy and splitting of water molecules into hydrogen and oxygen.
(iii) Reduction of carbon dioxide to carbohydrates

Figure 1. An excerpt from Grade X science textbook (National Council of Educational Research and Training, 2006)

What a teacher needs to do to effectively accomplish this adaptation -- where they are required to turn a static mechanism described in a textbook into a manipulable mechanism in the student's mind -- is manifold, very complex, and poorly understood, particularly in embodied cognition terms. For instance, to enable students to generate a manipulable mental model of the mechanism, teachers need to *re-enact the mechanism* in ways that build on students' (culturally situated) sensorimotor experiences. It is important to note here that reading out what is on the textbook is not enough to generate a mechanism in student minds, particularly in ways that enable students to mentally manipulate the mechanism. The mechanism needs to be re-enacted, drawing on the teacher's, and her students' sensorimotor experiences, in such a way that students will be able to replicate the mechanism accurately. However, the mechanism model formed in student minds, based on this culturally specific re-enaction, needs to closely follow the standardised version outlined in the textbook. To meet this dual requirement, teachers need to manipulate language and speech in ways that are predetermined (by the textbook), as well as spontaneous (to fit the students' mental simulation capabilities).

This simultaneously constrained and open process of acting out the mechanism is very complex, as the teachers may need to break the terminologies down, or modify them into sensorimotor constructs they deem more familiar to students. Such manipulation and enaction by a teacher may involve drawing on examples, analogies, metaphors, imagery and narratives. However, they have to ensure that the students will assemble these adapted components correctly, to form the right mechanism. In our ongoing project, we seek to develop an enactive cognition account of this complex dual process. It is worth noting here that very little is known about this process, and consequently, no technologies have been developed to either support this process, or train novice teachers to manage this process better.

T: So last class we were talking about… what were we talking about?
S: Events of photosynthesis
T: Events of photosynthesis and what were the events we discussed can you tell me in very short…
(The teacher continues to discuss two events of photosynthesis with the students.)
T: … so the third event is that carbon dioxide *(writing on the board)* third one CO2 I'm writing carbon dioxide gets reduced to carbohydrates we need to know only this much…
… you have to remember that is carbon dioxide gets reduced to carbohydrate. What is a carbohydrate here? What carbohydrate is being formed? The entire story…
S: Glucose
T: Glucose. Glucose is being formed right so CO2 gets reduced to carbohydrates this is the third step…
… it does not follow the sequence always as it is not necessary that only when the first will take place then the second will take place then the third will take place…

Figure 2. Transcript from a Grade X science classroom

Apart from language structures, the teacher's enaction of the mechanism employs extralinguistic moves, like gestures, diagrams, use of artifacts, modelling, and other guided activities. The teacher also evokes student responses, by asking questions. These teacher moves are intended to help students generate the new mechanism concepts, by extending their existing sensorimotor experiences, while simultaneously also associating the formal terms with these extended models.

Importantly, the 'teacher moves' employed to this end incorporate, as well as constantly probe, their model of the existing mind-states of the students. This process requires generating questions, observations and alternative sets of moves, as well as evaluating these to determine which combinations would best direct the modeled mind-state of the student, towards the desired mechanism direction. Based on this mind-modeling process, the teacher executes moves that they judge would bring students closer to the standard model of the mechanism concept, as given in the textbook. This modeling, judgements, plans and executions are performed in real time, and develop in interaction with student responses and the classroom environment. Developing a cognitive account of this complex and real-time teacher cognition -- which extends across mental models of student minds, textbook constructs, narratives, gestures, diagrams and artifact use -- is very challenging, as this requires bringing together ideas from distributed cognition, embodied cognition, and narrative theory.

Previous work that comes closest to characterising such teacher practice is Shulman's (1986) categorisation of a teacher's knowledge, into: 1) Subject Matter Content Knowledge, 2) Pedagogical Content Knowledge (PCK), and 2) Curricular Knowledge. PCK relates to what a teacher knows with respect to the teachability of a particular concept. This involves the ways in which a particular concept can potentially be represented, and the associated student-specific considerations. Shulman states, "Since there are no single most powerful forms of representation, the teacher must have at hand a veritable armamentarium of alternative forms of representation, some of which derive from research whereas others originate in the wisdom of practice."

This characterisation hints at a previously unexplored dynamic of representations that teacher actions are embedded within, and which results in a "wisdom of practice". This wisdom includes teachers' judgements of student preconceptions and misconceptions, and the ways teachers address these in instruction. This process requires making judgements about the mental states of the students, which is integral to teacher practice. Specifically, the teacher needs to access the student's enaction of the mechanism dynamics, based on cues in student responses. A two-way simulation dynamic thus ensues, wherein both the teacher and the student enact the other's mechanism, in interaction with each other. The PCK account does not delve into the cognitive mechanisms that underlie this dynamic.

We seek to develop an enaction-based process account of this type of teacher cognition, incorporating what is known from embodied cognition literature regarding modelling of other minds, particularly the embodied simulation theory of the mind (ESTM) and embodied simulation model of language (ESML). Developing such a model would help capture the dynamic nature of the teaching-learning process more systematically, as well as illustrate the cognitive complexity involved in good teaching. It could also lead us to understand how teachers enable mechanism concepts within student minds, and make technological access points available for optimising this process.

2. Operationalising the Problem

Science teaching requires teachers to model students' minds as they try to understand dynamics and mechanisms, which are captured and manipulated using symbolic entities, such as diagrams and equations. Such modeling of other minds, as they think with, and reason through, complex mechanisms, is very different from modeling just the *goals* of other minds. Specifically, the teacher's modeling of student minds involves three kinds of judgements:

1) *Judging students' ability to generate mechanisms in their minds.*

This involves generating a mental simulation of the dynamics/mechanism described in the curricular unit (oscillation, photosynthesis, vectors etc.), and actions/utterances that could help students start this simulation process, while parallely modeling the existing simulation capabilities of students.

2) *Judging how close student generated mechanisms are to some ideal set, often the one outlined in the textbook.*

This involves modeling the learner's mental operations, as the student works through problems that are based on the dynamics/mechanism. The teacher then needs to place the student's mental simulation in relation to an 'ideal' mental simulation, which would typically be the teacher's own. The key resources for this modeling are student errors, steps in worksheets, questions, and explanations provided by students. Based on these inputs, the teacher needs to build a second-order mental model, i.e. a mental model of each student's mental simulation.

3) *Judging which actions and utterances could move student-generated mechanisms to the ideal set, and judging the efficacy of these actions/utterances in real time, in relation to student responses and capabilities*.

This is the most difficult operation, as it involves real-time evaluation and revision. Here the teacher judges the difference between the student's simulation and the ideal one, to generate a set of questions, actions and utterances in real time, which could make the student's mental mechanism move towards the ideal mechanism.

All the three processes above are highly complex, and developing mechanism models of these processes require significantly extending our current understanding of how we come to know the states of other minds (Varma, McCandliss & Schwartz, 2008). In particular, the current models need to be extended in ways that would lead to a theory of how we can model other minds' learning states.

3. Possible mechanisms

The embodied simulation theory of mind would seek to model the above judgements using action-resonance, wherein an individual covertly enacts another's actions by mimicking them using one's own sensorimotor system (Gallese & Goldman, 1998). This process allows putting oneself in another's 'mental shoes', and thereby judge their mental states. The currently dominant neuroscience model of how we can execute this simulation process draws on action-resonance based on the mechanism of common coding (Hommel et al, 2001; Prinz, 2005). Resonating of others' actions using this mechanism is considered to provide information about other actors's goals, which are embedded in the action. Many studies support this model of knowing other minds (Umilta et al., 2001; Craighero, Leo, Umiltà & Simion, 2011), and it is thus a good starting point to develop models of teacher enaction.

However, it is not possible to smoothly extend this model to account for the above teacher enaction cases, as this theory does not have anything to say about how a teacher can judge whether a student has understood a mechanism, such as transpiration, correctly. This is because the student's actions do not allow the teacher to directly replicate the understanding of transpiration. The mental simulation of inanimate dynamics and mechanisms is very different from the simulation of actions -- even though parts of the action system, particularly activity in the pre-motor cortex, are reused to execute mental simulations of inanimate processes (Gallese & Lakoff, 2005; Schubotz, 2007).

A specific problem is the difference between mental simulations and goals. The student's actions, such as the movements involved in asking questions, could provide a sense of the student's goals, as they would be resonated by the teacher's action system. However, this resonance process cannot reveal the nature of the student's mental simulation of dynamics/mechanisms (such as transpiration), which is different from her action goals. To understand this mental simulation process, the teacher needs to run a second simulation in parallel, based on the content of the question asked by the student. This double-simulation process suggests that any model of teaching requires extending enaction-based theories of knowing other minds, to include language-based processes, such as questions, and narratives.

A second problem is developing an account of how teachers generate actions (diagrams, gestures) and utterances (narratives, questions) while enacting textbook material. To account for this enaction process, which is the starting point of students' mental simulation of dynamics/mechanisms, the current model of knowing other minds needs to be systematically connected to the way language and external representations (such as diagrams and gestures) are incorporated by the action system (Maravita & Iriki, 2004; Chandrasekharan & Nersessian, 2015; Chandrasekharan, 2016; Rahaman, Agrawal, Srivastava, Chandrasekharan, 2018).

The above discussion indicates that models of teachers' simulation of student mechanisms need to take into account many processes, based on language and other symbolic representations, such as student responses in classroom discussions and also exam questions. The embodied simulation model of language (ESML), which considers language as embedding sensorimotor elements (Bergen, 2015), could be a useful starting point to model this process. In this view, understanding the meaning of words and sentences involves activating modality-specific sensorimotor representations and processes. Neuroanatomical evidence grounds this activation in the sensorimotor neural circuits (Pulvermuller, 2010; Glenberg & Gallese, 2012). Supporting this approach, recent studies show that language can both trigger movements and incorporate movements (Pulvermüller, 2001; Glenberg & Kaschak, 2002; Matlock, 2004; Wilson & Gibbs, 2007; Bergen & Wheeler, 2010; Yee, Chrysikou, Hoffman, Thompson-Schill, 2013; Bub & Masson, 2012).

This view allows considering teacher and student language usage as embedding sensorimotor elements, and this embedding supporting the negotiation of meaning in the classroom (Salve, Narwal, Upadhyay, KK & Chandrasekharan, 2021). Extending the ESML model to the formation of mechanism concepts, the problem of students understanding teacher narratives about mechanisms could be understood as a process of running a dynamic mental model, where perceptual neural networks encoding experience help activate imagery (such as leaves, stems, stomata), and neural networks encoding motor experiences help 'dynamicise' this imagery (opening, closing, exchanging). Understanding of teacher narratives of mechanisms would thus involve running a simulation of the activity described by the narrative.

Based on the first encounter with the teacher narrative, a student may not be able to simulate the mechanism in all its complexity. Their simulation will be patchy and at a surface level, providing a summary understanding of the teacher narrative. For instance, in the case of transpiration, the student may not comprehend the opening and closing mechanism of the stomata as given, with all its details. But they may understand that there are pores in the roots, stem, and leaves of the plants, and there is some way in which the pores open and close, which allow some gases to be exchanged when the pores are open. Later, when the opening and closing of the stomata is invoked in another context, only this summary simulation will be activated. We use the term *gist simulation* to refer to such summary simulations (Salve et al., 2021). The nature of this simulation would vary a lot between students, depending on their real-world experiences and reading history.

Importantly, the gist simulation is an important consideration in a classroom context. The teacher, through their own understanding and experience of teaching a topic, as well as their knowledge of how a particular topic progresses in subsequent grades, settles on a particular level of gist simulation, which they enact, using the blackboard and gestures. This distributed enaction process, which is part of teachers' pedagogical content knowledge, helps class participants to converge their own individually-varied simulations to a common core, creating a shared understanding. The teacher can then build on this shared structure, to develop more complex discussions, and also evaluation parameters. The figure below captures how this simulation model could be used to understand classroom dynamics, in an integrated fashion, based on a series of hypothetical scenarios.

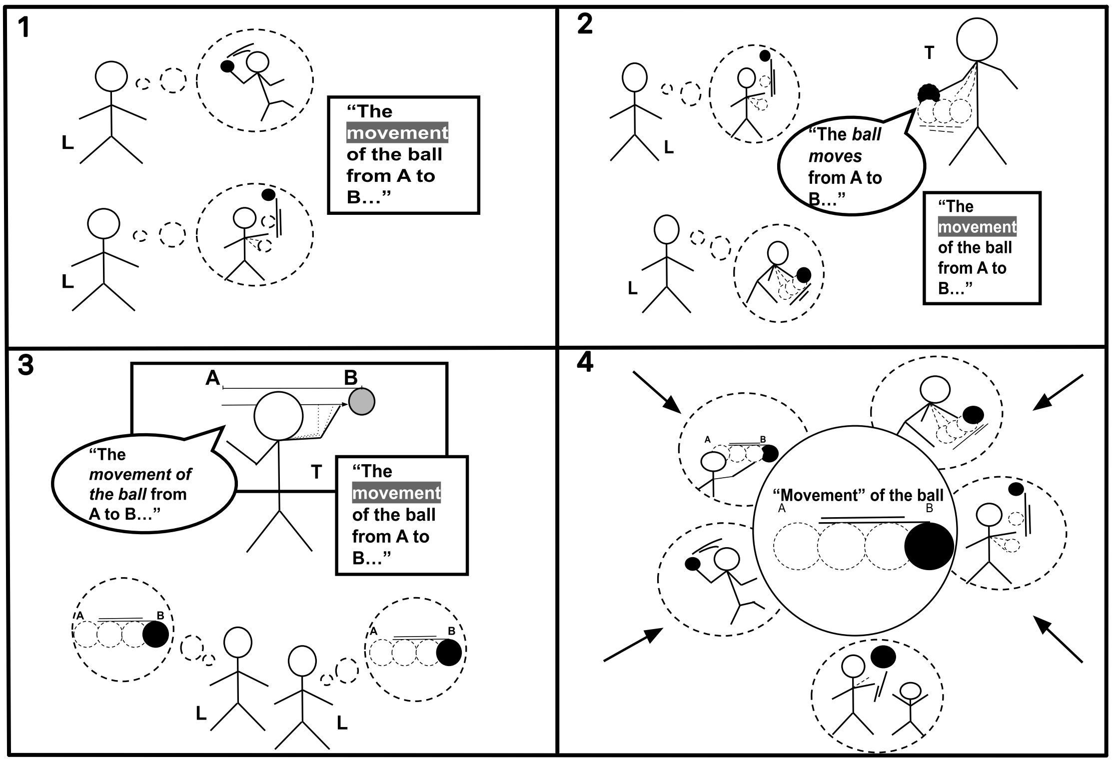

Figure 3. Panel 1 shows two learners with different simulations of the sentence [*The movement of the ball from A to B*]. Panel 2 and 3 shows the teacher enacting this sentence, using a ball and then the blackboard, and how this process changes the learners' simulations. Panel 4 shows different learners' simulations converging towards a gist simulation, modeled after the teacher's enaction.

A key theoretical objective of our current project is to develop a distributed and embodied cognition account of teacher enaction of mechanisms, combining simulation models of language, the way the action system incorporates external structures (Maravita & Iriki, 2004), and simulation-based judgement of others' mental states. In the ongoing phase, we seek to combine ESML with the embodied simulation of mental states, to develop an account of how teacher enaction leads to the formation of mechanism concepts, particularly in biology.

The following figure presents an approximation of teacher enaction of mechanism concepts, using four enaction stages (e1 to e4), commencing from the point at which the teacher forms their own gist simulation of the mechanism (e1). Students' in-class responses and ongoing evaluation, in addition to aggregated previous experiences of the teacher (with patterns of misconceptions/preconceptions in students), allow the teacher to build a model of the student's existing simulation of the mechanism (e2). Based on these, the teacher spontaneously generates possible alternative moves (e3), such as gestures, diagrams, etc. from their 'armamentarium'. They then choose a combination from these, in light of the contingencies that e2 presents. This stage is followed by the execution of a specific combination of these alternative moves (e4), for a specific student cohort. Any response that the teacher receives from the students in the form of doubts, questions etc. acts as feedback for the whole system (not just e4), and makes the process loop back to e2. This revises the teacher's perception of the student simulation of the mechanism, starting another teacher enaction cycle.

This entire process is very dynamic, and exists in a state of constant flux, co-evolving through the interaction between the teacher and the student. There is, however, value in understanding this dynamic in terms of stages such as the one we provide, as this can lead to analysis constructs and systematic models of teacher enaction. Current analysis emphasize the concrete/observable stages (e1 and e4), and thus implicitly promotes teacher training and technology designs that are focused on these stages. Our work focuses more on e2 and e3, and seeks to develop an embodied simulation account of both, and how they change in relation to e1 and e4. This shift in emphasis could lead to new kinds of teacher training and technology designs.

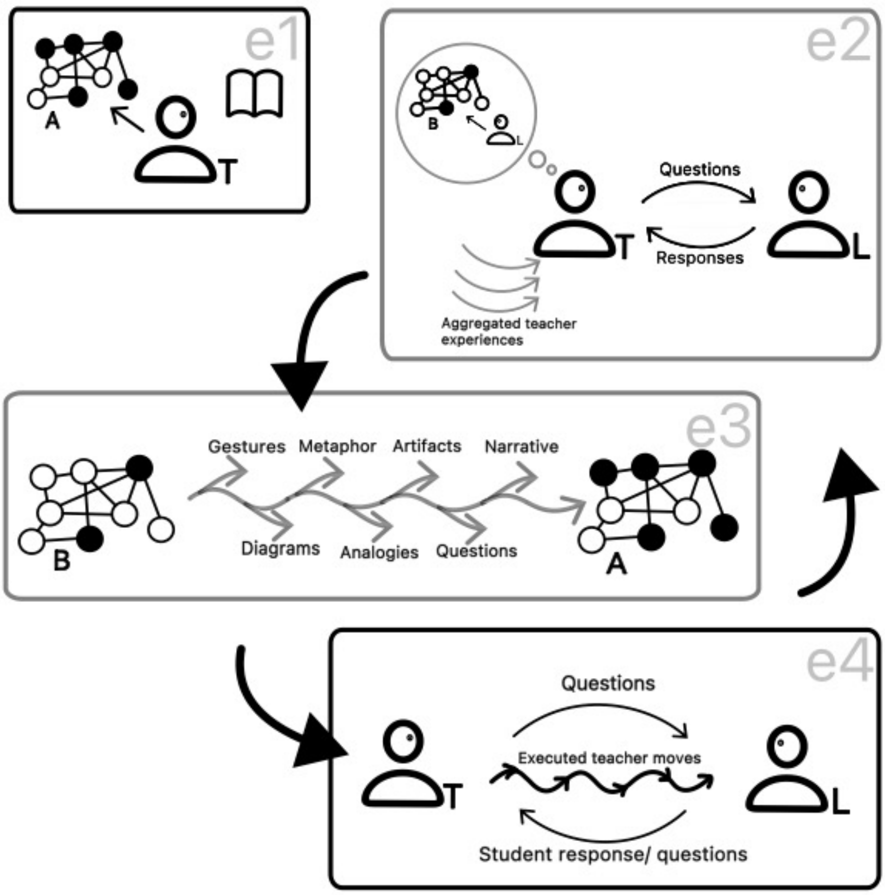

Figure 4: e1). Teacher's concept of mechanism, e2). Teacher's model of student mental state, e3). Teacher's selection of pedagogical strategies from the 'armamentarium', e4). Teacher's executed pedagogical strategy

To develop an analysis of teacher enaction based on this schematic, we are collecting video and interview data, of sessions where teachers enact different mechanisms for students. Students then explain their understanding of the mechanism to researchers. Based on this set of data, we seek to develop a model of how student simulation of mechanisms are revised by teacher enaction of mechanisms. This project will help understand how teachers develop the second order simulation (how students are simulating the mechanism/dynamics) based on student questions, descriptions, worksheet responses etc. It will also provide insight into the way teachers generate alternative actions/utterances, to guide students' simulations.

4. Possible Application Directions

Most technological interventions in education are focused towards addressing student difficulties. Such designs make the implicit assumption that the current pedagogical systems will eventually be replaced by technology-based ones. It is now increasingly clear that this implicit replacement model is not workable in most parts of the world, and instructional technologies will need to significantly accommodate existing teacher practices. While our group's previous work (Karnam et al., 2021) has illustrated and advocated this accommodative stance, we also consider it possible that the implicit replacement model may be an epiphenomenon – a by-product of cognitive theory focusing too much on learners' problems, and developing constructs that are heavily learner-centered, such as transfer, conceptual change, p-prims etc.

The work reported here is an effort to *also* bring into focus the cognitive mechanisms involved in the other side of the learning equation, specifically teacher enaction related to the teaching of complex dynamic mechanisms. We hope this discussion will help initiate a conversation on developing embodied learning technologies that are more focused towards helping teachers generate more productive enactions, as well as systematically track the effect of these technology-augmented enactions on students' understanding of mechanisms.

4.1. Teacher training

Besides the above translation to technological applications, the basic research advances from this analysis would also help address two longer-term application problems that are critical to education reform. The first problem relates to large-scale national-level policy changes in education, such as NGSS (Next Generation Science Standards, USA, 2013) and NEP (National Education Policy, India, 2020), which require teachers to radically upgrade their enaction practices in a short time, to implement these recommendations. Many studies show that teachers are not able to meet this unfair expectation (Batra, 2005; Cohen & Ball, 1990). Related to these policy changes, but at a smaller scale, teachers are also expected to adopt new educational technologies quickly into their teaching practices. Studies show that this adoption is also difficult for teachers (Bingimlas, 2009; Ertmer, 1999; Tsai & Chai, 2012).

A basic research model of teacher enaction, and related empirical methods, would be able to contribute significantly towards addressing these two problems, in the following ways:

1) by helping develop a clear understanding of the cognitive, affective and motivational factors that limit teachers' ability to meet policy expectations

2) by developing theory-driven guidelines that could help design systematic teacher training programs, focused on enabling teachers to upgrade their practices, including use of technology, to meet policy demands

We hope the analysis we report here will catalyse policy and technology discussions in this direction.

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