Performative Bundles: How teacher narratives reconfigure academic language, to help students build mental models

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DECLARATION

This thesis is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgment of collaborative research and discussions.

The work was done under the guidance of Dr. Mashood K. K at the Tata Institute of Fundamental Research, Mumbai.

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In my capacity as the formal supervisor of record of the candidate's thesis, I certify that the above statements are true to the best of my knowledge.

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Work related to the thesis

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Salve, J., Narwal, A., Upadhyay, P. Mashood, K. K., & Chandrasekharan, S. (2021). Learning to enact photosynthesis: Towards a characterization of the way academic language mediates concept formation. Proceedings of the Annual Meeting of the Cognitive Science Society, 43. Retrieved from https://escholarship.org/uc/item/9vf9k03h

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Abstract

This thesis explores how teachers construct dynamic mechanism models in students' minds, a complex process often hampered by the abstract nature of academic language (AL). The research, grounded in three studies, aims to illuminate the role of teachers in bridging the gap between abstract scientific concepts and students' concrete experiences.

The first study analyses teacher narratives that promote the learning of mechanism models, revealing the challenges posed by AL, particularly nominalization, which reifies abstract concepts as objects. Drawing on this analysis, the study proposes the "Performative Bundle" (PB) as a theoretical construct, integrating several enactive strategies teachers employ to connect abstract mechanism models with students' dynamic experiences. The PB model highlights the role of teachers as "seeders" of mechanism knowledge, carefully connecting abstract scientific concepts with students' everyday experiences, thus making the abstract more accessible and meaningful.

The second study extends the PB model to the domain of physics, examining how teachers build mechanism models (equations) in this discipline. This study extends the "loading of reality" view of scientific derivations, and also the concreteness fading view, emphasizing the gradual transformation of real-world phenomena into idealized mathematical representations. The study is based on an interactive system, which extends the PB model. The system helps students engage actively with the process of constructing physics models, bridging the gap between the concrete and the abstract. Study findings suggest that this system can help students internalize the 5-step sequence used in physics model-building. Further research is needed to assess its effectiveness in supporting the transfer of this knowledge to more complex problem-solving scenarios.

The third study investigates the connection between language structure and mental simulation, specifically focusing on how the grammatical structure of academic language, particularly nominalization, affects the distribution of attention. This study is based on a controlled experiment, and examines how changes in the grammatical structure of a text passage (e.g., increased nominalization) influences students' attention to local and global features, as measured by a divided attention task. The findings suggest that changes in linguistic structure, particularly nominalization, can influence how students mentally simulate scientific concepts and the perspectives they develop about the underlying processes.

The research primarily employs a case study methodology, and integrates both qualitative and quantitative data collection techniques. Interviews, classroom observations, and field notes provide rich qualitative data, while performance on tasks and reaction time in attention tasks provide quantitative data. These data are analysed through a framework that integrates multiple theoretical perspectives, including Embodied Simulation Theory of Language (ESTL), and Distributed Cognition, along with loading of reality and concreteness fading, allowing for a nuanced understanding of the complexities of the learning process.

This thesis contributes to the field of science education by illuminating the intricate relationship between language, cognition, and the construction of scientific knowledge. It underscores the importance of teachers' role in mediating this relationship, and proposes the PB model as a framework for understanding and improving the teaching of scientific mechanisms. The study highlights the potential of interactive technologies and a process-oriented approach to teaching and learning in science, fostering deeper understanding and engagement with complex scientific concepts. However, we acknowledge the limitations of the research, including the small sample size and the impact of the pandemic, and propose areas for future research and development, emphasizing the need for larger studies, more complex tasks, and greater involvement of teachers in the design and implementation of such interventions.

Chapter 1: Introduction

In this Chapter

It is very common to see students feeling challenged due to Academic Language (AL). There have been attempts to characterise the nature of this challenge. Nominalisation has been found to be an important characteristic and a ubiquitous feature of AL. Other features of AL have also been characterised. We discuss these characteristics and the role played by teachers in negotiating the challenges posed by AL, thus setting the premise of this thesis. We also discuss how AL features in Indian policy documents. The chapter ends with a brief summary of the thesis, including the way the thesis chapters are organised.

1.1 The Characteristics of AL and their role in Science Learning

Science learning requires learners to understand and internalise a new way of characterising reality. This new characterisation places several demands on the learner. While the cognitive demands of learning science concepts have been studied extensively, the linguistic demands of science learning have gained attention only in the last few decades. This recent focus is partly driven by classrooms becoming increasingly multilingual, and English language learners (ELLs) finding it particularly difficult to cope with the specialised disciplinary forms of language. Several curricular policy documents – such as the NGSS (NRC, 2013) (Next Generation Science Standards), the NCF (National Curriculum Framework) (NCERT, 2005) CCSS (Common Core State Standards) – have stressed the importance of Academic Language (AL) in learning, especially in the context of ELLs.

AL has been characterised in different ways, and for different purposes (Lemke,1990; Halliday, 2004, Anstrom, 2010). There is however no consensus on a clear definition of AL. It is broadly considered as a form of language that helps students acquire and use science and other formal knowledge. AL has been characterised from highly diverse perspectives, leading to multiple characterisations. Below we discuss some of the key characteristics and features of AL.

1.1.1 Nominalisation

Nominalization, a prominent feature of academic language, particularly in scientific writing, involves the transformation of verbs and adjectives into nouns, often abstract nouns. This linguistic process plays a crucial role in shaping the structure and meaning of academic texts, contributing to their characteristic density, complexity, and objectivity.

Halliday and Martin (2003) argue that nominalization is integral to the "discursive power" of science writing. By transforming dynamic processes into static entities, nominalization allows scientists to present their findings as objective and universal truths, rather than subjective interpretations. This process contributes to the authority and legitimacy of the field, as it distances the writer from the action and positions the knowledge as existing independently of individual perspectives.

Sfard (1991) further illuminates the complex relationship between processes and objects in academic discourse, arguing that they are two sides of the same coin. In this framework, nominalization can be understood as a linguistic strategy for transforming a process (verb), which is dynamic and embodied in action, into an object (noun), which is static and abstract. This transformation can obscure the underlying process and make it challenging for learners to fully grasp the meaning of the text.

However, the use of nominalization presents challenges for learners in academic contexts. The highly abstract nature of nominalized expressions can make texts dense and difficult to read and understand. Learners struggle to identify the underlying verbs and their associated meanings, which can hinder their comprehension and ability to engage with the text. Furthermore, mastering the use of nominalization in their own writing can be a significant hurdle for learners, requiring a deep understanding of the grammatical structures and the nuances of academic discourse. Apart from nominalisation, some of the other features of AL are discussed below.

1.1.2 More features of AL (Halliday, 2003)

In discussing the difficulties with AL, Halliday et.al. (Halliday, 2003) identify the following features as characteristic of AL. It may be noted that they do not claim this to be an exhaustive list.

1.1.2.1 Interlocking definitions

This is often observed in school science and mathematics texts, where to define something, a learner has to refer to already established definitions. For example, to define a diameter a learner would be expected to know what a radius, the centre or the circle is. The learner needs to be acquainted with a cluster of concepts in order to make meaning of the concept under consideration.

1.1.2.2 Technical taxonomies

Related to the above point, technical terms are typically organised in complex taxonomies. They have many layers of organisation built into them. Learners are rarely aware of such taxonomies as they are not made explicit. Also, the criteria on which they are based are not very clear to the students.

1.1.2.3 Lexical density

It gives a measure of how tightly the lexical items have been packed in the grammatical structure. The lexical density of AL is generally high compared to informal everyday language. Higher lexical density makes it difficult for students to understand a given passage.

1.1.2.4 Semantic discontinuity

In Scientific discourses writers often make semantic leaps. The reader is expected to follow through these leaps in order to reach the desired conclusion.

Consider the example below. After discussing the prevalence of the soot-coloured moth in industrialised England the following passage is written

However, strong anti-pollution laws over the last twenty years have resulted in cleaner factories, cleaner countryside and an increase in the number of light-coloured pepper moths.

The general structure of such statements is because ‘a’ happened ‘x’ happened. The happening of ‘a’ is logically connected to the happening of ‘x’. Here the students are expected to connect the introduction of strong anti-pollution laws with the related events that follow; such as cleaner factories, cleaner countryside and an increase in the number of light-coloured moths. The students are expected to make a semantic leap from the introduction of strong anti-pollution laws to light coloured moths in the process connecting it to/ figuring out the phenomena of natural selection. This often proves to be challenging for many students.

1.1.3 Some General Features

In addition to the features discussed above, two general features can be abstracted out of the discussions in the AL literature.

1.1.3.1 Decontextualisation:

One of the functional uses of AL is to convey precise, objective knowledge in a concise manner. As seen in the features above its grammatical structure has evolved to convey such specialised knowledge. The nature of objects that are described in AL is often removed from the context. Thus, the nature of the knowledge and the nature of entities described in AL lead to its decontextualization. Thus, decontextualization is an important feature of AL.

1.1.3.2 Freezing of dynamicity

Models and mechanism models of dynamic phenomena form an integral part of science. This gets reflected in the school science curriculum and STEM curricula in general. Several features of AL as discussed above contribute to the distinct structure of AL. Nominalisation converts process categories into object categories. The dynamicity of the process gets frozen in this conversion. This structure is useful to create complex networks of mechanisms, and higher order mechanisms.

Taken together, these features function to make understanding AL a formidable task for learners, particularly first-generation learners who do not speak English.

1.2 The challenges of AL and their accentuation in the Indian context

Taken together, the features discussed in Section 1 function to make understanding and using AL a formidable task for learners. From the perspective of Systemic Functional Linguistics (SFL), AL is characterised as a set of registers (Halliday, 2003), and its acquisition as socialisation into that register. This view also foregrounds the variability in the learners' familiarity with academic registers before they enter school. This variability correlates with the social location of the learner (Scheppegrell, 2012; Snow, 1983). This can be an important factor that reinforces social inequalities in the classroom. For instance, it is well-documented that learners from middle class families have more familiarity with the language of the school than those from working class families (Bernstein, 1971; Bordieu, 1984; Heath, 1983; Snow, 1983). Different approaches have been adopted to address this inequality. At one end of the spectrum, language simplification was adopted as a means to bridge the gap. While at the other end, it is argued that AL is an important skill to participate in academic practice (Lemke, 1990) and it must thus be explicitly taught as part of the school curriculum. In this view, simplification of AL may not serve any long-term purpose in the academic development of a learner.

Simplification however, appears in other guises in the classroom context. Teachers construct explanations to help learners understand the complex models embedded in the textbook discourse. Explanations become especially important in contexts where learners do not have access to educational resources apart from the teacher and the textbook. Simplification does not involve mere breakdown of complex words into their meanings or more familiar words, but promotes explanations that seek to channel what students already know, to make sense of the unknown. Here, teachers often make use of the learners' experiential resources, to familiarise them with the unfamiliar and abstract ideas presented in the textbook. Explanations are thus carefully constructed narratives that serve as a connecting bridge between students' experiences and abstract concepts in the textbook.

1.3 AL in Curriculum documents and policy

In the last few decades, the problem of academic language has gained importance in the curricular documents of many countries. In the Indian context, where most students have English as their second language, the national curriculum framework and the national education policy both advocate a mechanism for smooth transition from students' first language to the language of instruction. They however do not specify the explicit teaching of academic language in classrooms

Language features in the National Education Policy (NEP 2020) in primarily three respects: Foundational literacy and numeracy, Multilingualism and Promotion of Indian languages, arts and culture. NEP proposes the use of ‘home language/mother tongue’ as the medium of instruction at least up to middle school level. It states that:

All efforts will be made early on to ensure that any gaps that exist between the language spoken by the child and the medium of teaching are bridged.

The nature of this bridging is not well specified. Considering pedagogical aspects, it encourages teachers to use the students’ home language as the language of classroom transactions. It also proposes to make textbooks available in local and regional languages to facilitate learning.

The NEP distinguishes between home language and the language of instruction in the school, but lacks the resolution to distinguish between AL and EL. Thus, it does not consider the development of AL skills as part of its vision going forward.

Curricular Goal (CG-2) in the National Curriculum Framework on School Education (NCFSE) 2023 identifies “exploration of the physical world around them in scientific and mathematical terms” as an important goal to pursue. Apart from this, we could not identify anything that would directly connect to the use of AL. We expect our thesis to provide insights on navigating some of the recommendations made by these policies.

1.4 Making AL accessible - The role of teachers

In science education research much attention has been focussed on understanding the way students learn. The research on conceptual change and concept formation has been instrumental in this regard. The research on conceptual change has evolved from the initial consideration of students' concepts as rigid structures to their view as dynamic networks in a conceptual ecology. This evolution reflects the volume of work that has enriched the understanding of the students’ perspective in the learning process.

In contrast to the study of learners, very few studies have focused on the teacher’s perspective. A major contribution to the understanding of the teacher’s perspective comes from the literature on Pedagogic Content Knowledge (PCK) (Shulman, 1986). A majority of these studies have taken a static view of the teaching process. Here in this thesis, we adopt a dynamic view, drawing on and extending the Embodied Simulation Theory of Language (ESTL). This framework illuminates the dynamic processes by which the teacher builds mechanism models in students’ minds. The dual challenge that the teacher negotiates is due to the features of AL. In particular, we focus on teachers' role in making AL accessible to students, thereby helping them navigate science learning. Broadly this thesis examines the teaching and learning about models in a classroom – particularly mechanism models that are embedded in AL – from the ESTL perspective.

1.4.1 Bringing Action Back to the Discourse on Teacher Narratives

Extensive research in science education has examined the role student experiences play in sense making (Clark, 2006; diSessa, Gillespie, & Esterly, 2004; Carey, 2000; Chi, 2005; Ioannides & Vosniadou, 2002). However, a significant component of these studies is focused only on the cognition aspects of learning, and are mostly based on classical information processing models of cognition. The action dimension in student experiences has thus been ignored consistently. Actions form a fundamental aspect of our existence. We both act on the world as well as perceive actions. They are also an integral part of our language systems. The description of any event structure would not be complete without action elements. Actions crystallised in language, and their deployment in specific linguistic structures, forms a crucial aspect of academic discourse. This aspect is particularly relevant for AL, considering the characteristics of AL discussed earlier and the ensuing formidable learning challenges.

The enactive cognition framework prioritises actions, and it can thus provide an integrated account of the role of actions in learning. In learning science, empirical studies show how moving in new ways – based on designed technological contexts – can lead to new learning (Abrahamson, 2016). However, the interface between language and actions has not been studied very extensively within the larger 4E cognition model. Embodied simulation theory of language (ESTL), a theoretical framework under development, provides a way to address this gap (for a detailed review refer to Chapter 2). According to ESTL, understanding any text involves running a mental simulation of the events described in the text using language. The content of this simulation would draw from readers' embodied action experiences in the world. This account is based on studies of everyday language, which has evolved to describe the experiences of day-to-day life. This throws up interesting questions: what happens to these action experiences and everyday language as we shift to AL and formal academic contexts? How do students deal with this transition? What role does the teacher play in making this transition smooth? The following section explores the different roles the teacher assumes in this transition.

1.4.2 The Teacher as a Bridge

Students encounter abstract models and mechanism models embedded in AL in their textbooks. Due to the decontextualisation and the freezing of dynamicity brought about by the features of AL discussed above, they find it very difficult to make meaning from what they read. In contexts where access to technology is limited, apart from the textbook the teacher is the only resource available to gain this specialised knowledge. In such contexts the teacher has a challenging role to play. She has to contextualise these abstract models for the students, and also bring action back to the dynamic elements that are frozen due to the structure of AL. This has to be achieved within a limited technology space. Language remains the most readily available resource for the teacher in such contexts. She connects the experiences of the student with the abstract models in the textbook through language. The form of student experiences do not readily map to the content of the textbook. Often students are not aware of the existence of such a mapping, until it is made explicit to them. The teacher acts as a bridge in connecting these experiences to the abstract models in the textbook. She has to make precise and appropriate use of linguistic devices such as analogies, metaphors etc. for this purpose. This contributes in dynamicising the frozen dynamic concepts. This role of the teacher is discussed in more detail below.

1.4.3 Teacher as a De freezer / Animator

As discussed above, the dynamics of phenomena is frozen in AL. The teacher acts as a bridge connecting the learner's action experiences to the concepts to be understood. The teacher makes use of several enactive strategies to dynamicise these frozen models. When viewed from the framework of ESTL, language can thus be seen as a means by which sensorimotor simulations are activated (Please refer to Chapter 2 for a detailed discussion) and understanding is generated. The use of linguistic devices such as analogies maps the abstract concepts to the action based sensorimotor experiences of the learner. This mapping generates a correspondence between the structural features and action elements of the experience and the mechanism models. It thus dynamicises the mechanism models, drawing from learners' action experiences.

1.4.4 Teacher as a Compiler

The teacher does not just explain, she introduces the learner to the different representational forms of a discipline. She introduces the learner to the AL of the discipline. In doing so, she extends her roles as connector and as an animator to also act as compiler, wherein she compiles and pack these experiences, in ways that are linked to the abstract conceptual networks to be learnt. She also labels them appropriately, providing a systematic entry into the disciplinary AL. The teacher thus plays a dual role – breaking down and building up the mechanism models in a completely new way.

1.5 Brief summary of thesis and Outline of chapter organisation

As mentioned earlier, the focus of the thesis is on the teaching - learning of models, particularly mechanism models, in classrooms. We adopt an enactive cognition perspective, building on the Embodied Simulation Theory of Language (ESTL) and Distributed Cognition theory, to analyse episodes of classroom teaching of biology mechanisms. We propose 'Performative Bundles' (PBs) as a theoretical construct to analyse teacher narratives related to science. Specifically, PBs are a way to understand AL structures, such as formal terms used in science. Such terms are characterised as linguistic entities that embed teacher actions, which build multiple connections between students' known experiences and the unfamiliar science mechanisms that they need to learn. These connections can be based on analogical mappings, where the analogy used by the teacher during her explanation allows students to extend their own action experiences to mentally simulate the dynamics of unfamiliar and abstract science concepts, such as transpiration. The analogical structure can then be further extended, or combined with other representations, to generate more complex formal representational forms, such as cycles, equations, figures etc. Enactive elements used by the teacher during her explanation – such as gestures – also coalesce into the bundle. The formal terms used in AL are thus multilayered linguistic entities, supporting the running of mental simulations related to scientific mechanisms, which drive student understanding of the mechanism. A brief evaluatory study with practising teachers provided support for this new way to characterise teacher explanation of scientific mechanisms and related AL.

We extended the performative bundle idea, to develop an interactive simulation that embedded a novel way to teach physics derivations – as the 'loading' of real-world mechanisms into equations. This system was then presented to students. They were then asked to solve an unfamiliar physics problem. Their responses were tracked during problem-solving. Results showed that the new design, based on the characterisation of teacher narratives of AL as performative bundling, were helpful in advancing students' ability to solve novel problems.

We also developed an exploratory psychological study, using attention modulation as a probe, to understand the cognitive mechanisms involved in processing AL. Results provided indicative evidence for the proposal that the structure of AL significantly reoriented readers' attention.

1.5.1 Outline of the organisation of the chapters.

The thesis is organised into eight chapters. The first chapter spells out the complex interconnections between language, knowledge and understanding. It also sets out the background in which the problem of students' struggle with Academic Language (AL) is situated.

The second chapter reviews the literature related to teacher explanations, academic language, concept formation, and conceptual blending. This analysis characterises the differences in theoretical orientations, and identifies gaps in existing research. Placing the thesis as having a potential to fill these gaps we propose the thesis research questions. We provide an overview of the theoretical frameworks adopted for the analysis of AL. As the analysis we provide draws on multiple ideas within the embodied and distributed cognition framework, we provide a summary of these approaches, and describe the various ways in which these ideas intersect, and also present them as a whole.

The third chapter provides a rationale for choosing a particular methodology over others, to address the research questions. It summarises the different data collection methods used across the three studies.

Chapter four provides an analysis of teacher explanations of different biology mechanism models related to photosynthesis. We analyse multiple teaching episodes, identified from transcripts of audio recordings of classroom observations.

The fifth chapter discusses the extension of the PB approach, to develop an interactive simulation that seeks to help teachers teach the building of physics derivations, and allow students to build a systematic mental model of this process.

Chapter six presents a psychological study exploring the complex inter-relations between academic language, student understanding and attention. This study of student cognition was conducted using the context of biology mechanism models.

In the seventh chapter we draw conclusions from the above three studies, and explore some of their implications. Here, we also discuss the limitations and the future ways in which these studies can be extended.

Chapter 2: Literature Review

In this Chapter

In this thesis we investigate the construction of mechanism models by teachers through different strategies that they use in the classroom. In particular we focus on the role of academic language (AL) in the whole process. This chapter reviews literature relevant to our research, organised broadly into 2 parts - the first part focusing on AL (Sections 2.1 and 2.2) and the second on different frameworks of cognition (Sections 2.3 and 2.4). The research on AL has gained traction in recent years. It has been explored through different theoretical frameworks. Here we review three major frameworks that explore the different dimensions of AL. Systemic Functional linguistics explores both the grammatical structure as well as the functional use of language across diverse contexts. The cognitive linguistic frameworks of conceptual metaphor and conceptual blending are also reviewed to explore the theorising of AL and the teaching of mechanism models. Critical perspectives on each of these frameworks are also discussed. The gaps identified in this literature motivated the thesis research questions. In the second part of the chapter, we review different frameworks of cognition ranging from the information processing paradigm to the framework of Embodied simulation theory of language (ESTL). We end the review with a discussion of the framework of distributed cognition, within which we locate the theoretical framework of our study.

2.1 Academic Language Development for English Language Learners (ELLs)

Academic language, distinct from everyday conversational language, is essential for students' success in school. This specialised language includes complex vocabulary, syntax, and discourse features required for engaging with academic content in areas such as mathematics, science, and social studies. English Language Learners (ELLs), are learners whose home language is not English. They face the dual challenge of learning English as well as its academic registers. Mastery of academic language is critical for their success across the curriculum. This review synthesises key findings from a broad range of research, exploring various dimensions of academic language, including definitions, instructional strategies, literacy development, cross-disciplinary skills, and the challenges ELLs encounter.

2.1.1 Defining Academic Language

Academic language has been defined in multiple ways in the literature. Scarcella (2003) describes it as a complex, abstract, and specialised form of communication that differs significantly from conversational language. It encompasses features like advanced vocabulary, sophisticated grammatical structures, and cohesive devices used to express complex ideas. Gottlieb and Ernst-Slavit (2014) highlight that academic language is multidimensional, varying across disciplines, and essential for accessing content knowledge in subject areas like mathematics, science, and history.

Cummins (2000) distinguishes between Basic Interpersonal Communication Skills (BICS) and Cognitive Academic Language Proficiency (CALP), emphasising the importance of understanding academic language as more than just vocabulary. BICS refers to everyday conversational skills that students acquire relatively quickly, while CALP involves the cognitive and linguistic skills required for academic tasks, such as reading complex texts or writing research reports. Cummins argues that academic success for ELLs requires a shift from conversational proficiency to more sophisticated academic language use.

2.1.2 The Role of Academic Language in Literacy Development

The relationship between academic language and literacy development has been a key area of focus. Nagy and Townsend (2012) argue that academic vocabulary is a fundamental tool for learning to read and write in academic contexts. Mastery of academic vocabulary allows students to comprehend and produce written texts across subjects. Their work emphasises that vocabulary acquisition is not just about memorising definitions but understanding how words function within complex academic texts.

Connor et al. (2015) add a nuanced layer to this view, by exploring individual differences in literacy development through eye-movement studies. Their research shows that students with stronger academic language skills exhibit better comprehension monitoring, a key component of reading comprehension. This suggests that academic language is deeply intertwined with literacy and should be a focal point of instructional interventions aimed at improving reading outcomes for ELLs.

Proctor et al. (2020) examine how language-based reading interventions specifically targeting academic language and reading comprehension impact ELLs. Their study finds that interventions focusing on both linguistic and cognitive aspects of reading significantly improve students’ academic language and comprehension. This finding aligns with Snow’s (2010) assertion that science education, in particular, demands a specialised academic language that students must master to engage deeply with content.

2.1.3 Instructional Approaches to Academic Language Development

Several instructional models have been developed to address the challenges of teaching academic language to ELLs. Chamot and O’Malley (1996) proposed the Cognitive Academic Language Learning Approach (CALLA), which integrates content learning with explicit language instruction. This approach emphasises the teaching of learning strategies alongside subject matter, supporting ELLs in acquiring both academic language and cognitive skills. CALLA is particularly effective in linguistically diverse classrooms, where students are learning content in a second language.

Zwiers (2006, 2007) also explores the integration of academic language with content learning through scaffolded instruction. He emphasises the need for teachers to explicitly teach academic vocabulary, sentence structures, and discourse forms that students will encounter in subject-specific texts. Zwiers' research highlights how scaffolding—providing temporary support to help students bridge gaps in their knowledge—can be particularly beneficial for middle-grade students learning academic content in their second language. This aligns with Truckenmiller et al. (2019), who also advocate systematic approaches to academic language instruction across grade levels, stressing the need for teachers to explicitly focus on language features necessary for understanding and producing academic texts.

Short, Fidelman, and Louguit (2012) provide further evidence supporting the effectiveness of sheltered instruction for ELLs. Sheltered instruction involves teaching academic content in a way that makes it accessible to students still developing proficiency in English. The SIOP model (Sheltered Instruction Observation Protocol) is a widely used framework that integrates content and language instruction, by incorporating academic language objectives into content lessons. The model ensures that ELLs simultaneously develop language skills while engaging with subject-specific content, which is particularly important for students in middle and high school, where the academic demands increase.

2.1.4 Cross-Disciplinary Academic Language Skills

The development of academic language is not confined to any single discipline. Research has increasingly focused on the cross-disciplinary nature of academic language, with scholars like Phillips Galloway et al. (2020) and Fitzgerald et al. (2020) emphasising the importance of academic language skills across subjects such as science, mathematics, and social studies. Phillips Galloway et al. (2015) found that strong lexico-grammatical and discourse organisation skills in middle-grade students significantly enhance their writing abilities across disciplines. Their research demonstrates that students' ability to organise complex ideas in writing is supported by mastery of academic language features common to multiple subjects.

Fitzgerald et al. (2020, 2022) explore the development of academic vocabulary networks in elementary textbooks across various disciplines. Their findings reveal that disciplinary texts at the elementary level expose students to a wide range of academic vocabulary, underscoring the need for intentional instruction that is focused on helping students understand and use this vocabulary effectively. This research points to the importance of embedding academic language development within content-area instruction from an early age, preparing students for more advanced academic tasks in later grades.

The cross-linguistic contributions of academic language skills are also noteworthy. Phillips Galloway et al. (2020) explore how Spanish and English academic language skills interact in bilingual learners, showing that cross-linguistic academic language proficiency significantly impacts reading comprehension in English. This highlights the importance of recognizing the linguistic assets that bilingual students bring to their academic learning and underscores the need for instructional approaches that build on students' existing linguistic knowledge.

2.1.5 Challenges and Opportunities in Academic Language Development for ELLs

Despite the significant progress made in understanding and supporting academic language development, ELLs continue to face challenges. Valdés (2004) addresses the tension between providing adequate support for ELLs and avoiding marginalisation. She argues that while targeted academic language instruction is essential, care must be taken to ensure that ELLs are not segregated from mainstream educational opportunities. Valdés (2004) emphasises the need for inclusive practices that support academic language development while promoting integration into the broader educational community.

Anstrom et al. (2010) and DiCerbo et al. (2014) provide comprehensive reviews of strategies for teaching academic English to ELLs, identifying key practices such as explicit vocabulary instruction, the use of academic discourse in classroom interactions, and the integration of academic language objectives into content-area instruction. Their reviews highlight that effective academic language instruction requires a multifaceted approach, combining content knowledge with language development and addressing the diverse linguistic needs of ELLs.

The literature on academic language development offers a detailed and nuanced understanding of the challenges and opportunities for ELLs in K-12 settings. Academic language is a multifaceted construct that plays a crucial role in students' ability to access and engage with content across disciplines. Effective instructional approaches—such as CALLA, sheltered instruction, and scaffolded teaching—can significantly enhance ELLs’ academic language skills, leading to improved literacy and content learning outcomes.

2.1.6 English as a second language in the Indian context

English as a medium of education in India, particularly in professional and multilingual contexts holds a dual role as a tool for global integration and as a symbol of social stratification. The literature explores its impact on science education, challenges in professional education, and cultural interplays in language learning, particularly in multilingual settings. This review synthesizes findings from works examining the role of the English language in education, focusing on multilingualism, engineering pedagogy, and learner challenges.

Research has investigated the role of English through the lens of power. The dominance of English in Indian education is critiqued as a "medium of power” (Annamalai, 2004). This work illustrates how English perpetuates social inequalities by favouring elites who have easy access to quality English-medium education. It underscores the exclusion of local languages in formal education, leading to cultural and linguistic alienation for non-English-speaking students. English dominates over mother tongues forming a linguistic hierarchy, leading to "multilingualism of the unequal's" (Mohanty, 2006). In addition, this study emphasizes the pedagogical importance of mother tongue instruction, advocating for equitable multilingual education systems. Pandey and Jha (2023) delve into the cultural dynamics of learning English as a second language in India. Their findings suggest that cultural contexts influence learning styles and language acquisition. This cultural lens helps bridge the gap between learners' environments and educational goals.

Gupta (2013) and Patra and Mohanty (2016) examine English's role in engineering education. While English facilitates access to global resources, its poor implementation often hampers technical comprehension among students. While Gupta (2013) emphasizes curriculum deficiencies, recommending a focus on technical English skills, Patra and Mohanty (2016) evaluate the effectiveness of current teaching methods, finding a gap between industry needs and classroom instruction.

In a study that explores the psychological dimension, anxiety is highlighted as a significant barrier in second-language acquisition for engineering students (Saranraj & Meenakshi, 2016). The study suggests interventions like confidence-building exercises to improve language proficiency.

Despite research efforts that highlight various challenges faced by English language learners in the Indian context, not much has translated into policy making. There is a disconnect between policy and practice regarding English in science education (Bansal, 2022). Teachers' orientations significantly affect how policies translate into classroom practices. This research reveals the dominance of English as a teaching medium marginalizes non-English speakers, impacting their scientific understanding and learning outcomes.

There is however a need to explore the cross-disciplinary nature of academic language, focusing on how academic language skills developed in one content area can transfer to others. Additionally, more attention is needed on how to support ELLs in developing academic language without isolating them from mainstream educational experiences, ensuring that all students have access to academic opportunities. Facilitating this requires an in depth understanding of the different dimensions of AL. In the next sections 2, 3, 4 and 5 we review three major frameworks that explore various dimensions and facets of AL.

2.2 Systemic Functional Linguistics (SFL) and Its Application in Academic Literacy

The study of academic literacies and systemic functional linguistics (SFL) has garnered attention for its potential to analyse and enhance language instruction, particularly in academic settings. SFL, a theory of language developed by Michael Halliday (1995), views language as a social semiotic system that functions to make meaning across contexts. The application of SFL in educational contexts, particularly in relation to academic literacies, focuses on developing students' ability to use academic language effectively. This literature review synthesises the key research on SFL and its pedagogical implications for academic literacies, drawing on recent studies that explore how SFL supports the development of academic writing and critical thinking.

2.2.1 Overview of Systemic Functional Linguistics

Systemic Functional Linguistics (SFL) emphasises the functional role of language in context, focusing on how language constructs meaning in social interactions. According to Eggins (2004), SFL views language as operating across three meta functions: the ideational, interpersonal, and textual. The ideational metafunction refers to how language represents experiences and ideas, the interpersonal metafunction deals with social interactions and relationships, and the textual metafunction addresses the organisation of language into coherent discourse. These functions help explain how academic language is structured and used in educational contexts.

SFL is closely tied to the concept of register, which Matthiessen (2019) describes as the variation in language use depending on the context of the situation, including field (the subject matter), tenor (the participants and their relationships), and mode (the channel of communication). Register is particularly relevant in academic contexts where language must adapt to the specialised demands of different disciplines.

2.2.2 Academic Literacies and SFL

Coffin and Donohue (2012) discuss how SFL intersects with academic literacies, which focus on the social and cultural practices of writing in academic contexts. While academic literacies highlight the importance of understanding power dynamics and institutional norms in academic writing, SFL provides a detailed grammatical framework that helps students understand how these norms are realised in language. Coffin and Donohue (2012) suggest that combining these approaches enables students to navigate the complex linguistic demands of academic tasks more effectively.

Building on this, Martin (2016) traces the evolution of SFL and its application in educational settings, noting that its expansion beyond clause-level analysis to text-level and genre-based approaches has been instrumental in academic literacy studies. Academic genres, such as essays or scientific reports, each have distinct linguistic structures that students must master to succeed in their academic writing. SFL provides a framework for analysing these structures and helping students produce texts that meet academic expectations.

2.2.3 SFL and Teacher Education

One of the key areas where SFL has had a significant impact is teacher education. Gebhard (2010) emphasises the importance of SFL in preparing teachers to support students' academic language development. By understanding how language functions to make meaning, teachers can better scaffold students' use of academic language. Gebhard (2010) argues that knowledge of functional grammar enables teachers to provide explicit instruction in how to construct academic texts, which is particularly beneficial for linguistically diverse students.

Daniello, Turgut, and Brisk (2014) extend this argument by demonstrating how SFL can be used to build educators' knowledge of academic English, especially for teaching writing in multilingual classrooms. Their work highlights how SFL can guide teachers in helping students make informed linguistic choices, which align with the disciplinary conventions of academic writing.

2.2.4 SFL in Science Education

SFL has also been applied extensively in subject-specific contexts, particularly in science education. O'Hallaron, Palinscar, and Schleppegrell (2015) use SFL to analyse how scientific texts present complex ideas. They argue that by focusing on the ideational metafunction, students can better understand how scientific knowledge is constructed through language. This is crucial for developing critical language awareness, as students often struggle to comprehend the dense and abstract nature of scientific discourse.

2.2.5 Multilingual and Culturally Sustaining Pedagogy

The role of SFL in supporting multilingual students is explored in the work of Sembiante and Tian (2021), who argue that SFL can be integrated with culturally sustaining pedagogy to support academic language development in diverse classrooms. They propose that SFL, with its focus on meaning-making in context, provides a framework for analysing how students from different linguistic and cultural backgrounds construct knowledge in academic settings. This approach not only helps students learn academic content but also values their linguistic and cultural identities.

In a similar vein, Siffrinn and Harman (2019) propose an embodied approach to SFL pedagogy, which emphasises the use of multimodal and physical practices to teach academic language. They argue that academic language is not just about grammatical correctness but also involves the use of gestures, visuals, and other embodied practices to communicate meaning. This approach is particularly relevant in multilingual classrooms, where students may use multiple modes of communication to express academic concepts.

2.2.6 Critiques and Future Directions

Despite its widespread application, SFL has faced criticism. Martin (2014) acknowledges that while SFL provides a detailed analysis of language function, some scholars argue that it can overlook the broader social and cultural factors that shape language use. Critics suggest that SFL needs to engage more deeply with issues of power, identity, and access to academic discourse, particularly for marginalised students.

In response to these critiques, Salam, Mahfud, and Nurhusna (2018) emphasise the importance of linking SFL with critical pedagogy to address issues of equity in education. They argue that SFL should not only focus on linguistic analysis but also consider how academic language practices can either empower or marginalise students.

Systemic Functional Linguistics offers a powerful framework for analysing academic language and supporting students in developing the linguistic skills needed for academic success. Its application in academic literacies, teacher education, science education, and multilingual contexts highlights its versatility and relevance in contemporary education. However, as scholars continue to explore the intersection of SFL with critical pedagogy and culturally sustaining approaches, it is important to consider how SFL as a macro lens in analysing linguistic phenomena can be integrated with more fine-grained approaches such as cognitive linguistics to provide a more holistic understanding of such phenomena. In the next sections (3 and 4), we review two major theoretical approaches within cognitive linguistics – conceptual metaphor and conceptual blending – and the role they play in driving teaching and learning across different contexts.

2.3 Conceptual Metaphor Theory in Education

Conceptual Metaphor Theory (CMT), introduced by Lakoff and Johnson (1980), has become a significant framework for understanding how abstract concepts are comprehended through metaphorical thinking. Metaphors allow individuals to understand one conceptual domain in terms of another, bridging the gap between abstract and concrete knowledge. In the realm of education, CMT has provided valuable insights into how learners grasp complex concepts, particularly in science and mathematics, and how teachers use metaphors to convey these concepts. This literature review explores the application of CMT in various educational contexts, drawing from multiple studies on its use in teaching, learning, and conceptual change.

2.3.1 Conceptual Metaphor in Teaching and Learning

Metaphors serve as cognitive tools that shape how educators and learners conceptualise and navigate the learning process. Alger (2009) examines how secondary teachers’ metaphors of teaching and learning evolve over the span of their careers, revealing shifts in how they view their role and responsibilities. Similarly, Saban (2006) highlights the importance of metaphor in teacher education, proposing that metaphors not only reflect teachers' personal philosophies but also influence their instructional practices.

Amin (2009, 2017) expands on the idea that metaphors play a pivotal role in conceptual change, especially in science education. His research demonstrates how metaphors can facilitate or hinder students' understanding of scientific concepts by framing them in familiar or unfamiliar terms. Furthermore, Danesi (2003, 2007) explores how CMT can be applied to mathematics education, showing that metaphors help students grasp abstract mathematical ideas by relating them to everyday experiences. The pedagogical use of metaphors, as suggested by Yee (2017), is also key in mathematical problem solving, where both teachers and students employ metaphors to simplify and engage with challenging concepts.

2.3.2 Conceptual Metaphor and Embodied Cognition in Science Education

The connection between conceptual metaphor and embodied cognition, which suggests that cognitive processes are deeply rooted in bodily experiences, has been explored in the context of science education. Amin, Jeppsson, and Haglund (2015) investigate how metaphors and embodied cognition interact to shape students' learning experiences in science. Their research indicates that metaphors are not only linguistic expressions but also tied to sensory and motor experiences, allowing learners to build a more integrated understanding of scientific concepts.

The work of Corni, Fuchs, and Dumont (2019) further supports the use of visual and analogical metaphors in physics education, providing concrete examples of how student teachers can use these metaphors to explain abstract concepts. Similarly, Daane et al. (2018) emphasise the pedagogical value of metaphors in secondary science education, showing that effective use of metaphors can enhance students' engagement and comprehension of difficult scientific principles.

Niebert and Gropengiesser (2017) offer a framework for understanding external representations in science teaching through the lens of conceptual metaphor. They propose that the "mesocosm"—the middle ground between the macro and micro levels of scientific phenomena—serves as a conceptual space where metaphors can be applied to bridge students' understanding of abstract scientific theories.

2.3.3 Metaphors in Conceptual Change and Cognitive Linguistics

Conceptual metaphors are not static; they evolve as individuals' cognitive structures change. According to Amin (2009), conceptual metaphors can either facilitate or impede conceptual change depending on how well they align with learners' prior knowledge and experiences. This view is echoed by Conrad and Libarkin (2022), who employ CMT within the Model of Educational Reconstruction to identify students' alternative conceptions in geology education, particularly in the context of plate tectonics. Their findings suggest that addressing misconceptions through metaphors can improve students' grasp of scientific concepts.

Geeraerts (2006) and Gibbs (2009, 2011, 2014) provide a broader perspective on CMT within cognitive linguistics, discussing how metaphors are fundamental to human thought and communication. Gibbs, in particular, critiques and evaluates CMT’s explanatory power, arguing that metaphors extend beyond language to shape social actions and cognitive processes. His work highlights the importance of evaluating how metaphors influence not just individual cognition but also collective understanding in educational settings.

2.3.4 Applications of Conceptual Metaphor in Diverse Educational Contexts

The application of CMT is not limited to science and mathematics education. Harper, Tran, and Cooper (2024) demonstrate the utility of metaphors in computing education, where students' understanding of abstract computing concepts is enhanced through metaphorical frameworks. Pérez (2017) applies CMT to language learning, suggesting that teaching conceptual metaphors in English as a Foreign Language (EFL) settings can improve learners' comprehension of idiomatic expressions and cultural nuances.

The interdisciplinary nature of CMT is further explored by Pourcel and Evans (2009), who introduce new directions in cognitive linguistics, including the role of metaphor in cross-linguistic and cross-cultural studies. This broader application of CMT in education underscores its versatility as a tool for fostering deeper understanding across different domains of knowledge.

2.3.5 Criticisms and Alternative Approaches to Conceptual Metaphor Theory

Despite its widespread use, CMT has faced criticism from scholars who question its explanatory power. Kövecses (2008) provides a critical review of CMT, suggesting that while the theory is useful in understanding conceptual structures, it may oversimplify the complexity of human cognition. McGlone (2007) adds to this critique by questioning whether conceptual metaphors truly provide a deeper understanding of abstract thought or merely offer convenient linguistic shortcuts.

Nonetheless, Vervaeke and Kennedy (2004) argue that conceptual metaphors play a crucial role in abstract thinking, particularly in higher-order cognitive processes. Their research highlights the value of metaphorical thinking in developing complex ideas, suggesting that while CMT may have limitations, it remains a powerful tool for understanding cognitive processes in educational contexts.

Conceptual Metaphor Theory has made significant contributions to the field of education by providing a framework for understanding how abstract concepts are taught and learned through metaphorical thinking. From science and mathematics to language learning and computing, metaphors serve as essential cognitive tools that shape learners' comprehension of complex ideas. While criticisms of CMT suggest the need for further refinement, the theory's application across diverse educational domains demonstrates its enduring relevance and potential for fostering deeper understanding. As research on CMT continues to evolve, future studies may explore new ways of integrating metaphorical thinking into educational practices to enhance student learning outcomes.

2.4 Conceptual Blending

Conceptual Blending Theory (CBT), pioneered by Fauconnier and Turner (Fauconnier & Turner, 1998), provides a cognitive framework for understanding how individuals merge different mental spaces to create new meanings, ideas, and solutions. This framework is used across various domains, including education, science, design, and linguistics. Conceptual blending involves the combination of abstract and concrete inputs into "blends" that facilitate creativity, problem-solving, and meaning-making. This review synthesises key research on conceptual blending and its application in education, science learning, and design ideation.

2.4.1 Conceptual Blending in Education

Conceptual blending has significant applications in education, particularly in helping students understand complex and abstract concepts. Fredriksson and Pelger (2020) explore how students use metaphorical concepts in science education, illustrating how conceptual blending enables learners to engage with and comprehend intricate scientific ideas. Gregorcic and Haglund (2021) apply conceptual blending as an interpretive tool for understanding students' interactions with technology, particularly in their exploration of celestial motion on an interactive whiteboard. This work highlights the role of blending abstract scientific principles with digital tools to enhance student engagement and learning.

Odden (2021) investigates the use of conceptual blending in introductory physics, revealing how students create blends to make sense of complex physics principles. Similarly, Hu and Rebello (2013) explore how students employ conceptual blending when using mathematical integrals in physics, demonstrating that blending abstract mathematical concepts with physical scenarios improves problem-solving. These studies show that conceptual blending plays a critical role in helping students develop a deeper understanding of scientific and mathematical concepts.

2.4.2 Cognitive Mechanisms of Conceptual Blending

The cognitive processes underlying conceptual blending are essential for understanding how learners construct meaning across disciplines. Fauconnier (1998) introduces the idea of conceptual integration networks, which allow learners to combine disparate inputs into a new mental space. This cognitive mechanism is central in educational settings, where students must often blend new information with prior knowledge to generate meaningful understanding. Fauconnier and Turner's (2011) work on polysemy and blending underscores the flexibility of language and meaning construction, which is highly relevant in educational environments that require creative thinking and problem-solving.

Coulson (2001) emphasises the role of frame-shifting in conceptual blending, where learners shift between different mental frameworks to construct new meanings. This process is critical in education, as students frequently encounter novel concepts that challenge their existing knowledge structures. Coulson (2008) expands on this by discussing how conceptual blending shapes rhetoric, thought, and ideology, further underscoring the cognitive flexibility required for meaning-making.

2.4.3 Conceptual Blending in Science and Mathematics Education

In the realm of science education, conceptual blending offers a lens to understand how students navigate complex ideas. Dreyfus, Gupta, and Redish (2018) apply conceptual blending to model how students use multiple ontological metaphors in science learning, showing that blending metaphors helps students better understand abstract scientific concepts. Eynde et al. (2020) use dynamic conceptual blending analysis to study student reasoning in physics, particularly in the context of the heat equation, and illustrate how blending supports interdisciplinary thinking across mathematics and physics.

Hoehn, Finkelstein, and Gupta (2016) use conceptual blending to analyse group discourse in science education, revealing how students collaboratively construct blends that enhance their collective understanding of scientific problems. These studies collectively demonstrate the value of conceptual blending as a tool for enhancing student reasoning, fostering interdisciplinary connections, and improving problem-solving in science education.

2.4.4 Conceptual Blending in Design and Creativity

In addition to education, conceptual blending is widely used in design and creative problem-solving. Biskjaer et al. (2018) investigate how materials support conceptual blending in ideation during the design process, emphasising how tangible resources help designers generate creative solutions by blending abstract and physical elements. Similarly, Wang (2014) uses conceptual blending to analyse the design process, highlighting how designers merge different conceptual inputs to create innovative solutions.

Hutchins (2005) expands on the role of "material anchors" in conceptual blending, showing how physical objects can stabilise abstract blends. This is particularly relevant in design and education, where physical representations play a key role in helping learners and creators understand and manipulate abstract ideas. Oakley (1998) also examines conceptual blending in narrative discourse and rhetoric, focusing on how individuals blend narrative structures to craft persuasive arguments and creative narratives.

Markauskaite and Goodyear (2017) extend the concept of blending to multimodal learning environments, where students integrate visual, auditory, and kinesthetic inputs to form cohesive understandings. Ligorio et al. (2011) similarly explore how blended learning activities can be designed by integrating different educational models, illustrating how conceptual blending can be applied to create effective learning experiences that combine traditional and digital learning environments.

2.4.5 Conceptual Blending and Frame-Shifting

Frame-shifting is a crucial component of conceptual blending, particularly in educational and rhetorical contexts. Coulson (2001) explores how frame-shifting facilitates conceptual blending, allowing learners to navigate between different mental spaces and construct new meanings. Turner (2007) introduces the notion of frame blending, where multiple narrative or conceptual frames are merged to create novel interpretations. This process is essential for creative thinking, problem-solving, and meaning-making in both educational and design contexts.

Conceptual Blending Theory provides a robust framework for understanding how individuals merge abstract and concrete concepts to generate new meanings. In education, conceptual blending facilitates student engagement with complex scientific and mathematical concepts, while in design, it supports creative ideation and problem-solving. Across these domains, conceptual blending enhances learners' ability to reason across multiple cognitive spaces, fostering deeper understanding and interdisciplinary thinking.

2.5 The features of teacher explanations

Though the three frameworks on AL discussed in the previous sections - Systemic Functional Linguistics, Conceptual Metaphors and Conceptual Blending – provide valuable insights on their own, their role and impact on teacher education has been limited. Teacher explanations is a potential area where these insights could have been applied, but the literature on teacher explanations does not show many instances where inputs from these diverse theoretical orientations have been incorporated.

Dagher and Cossman (1992) create a typology of teacher explanations based on classroom observations. They observe wide variation in the use of these ten different types of explanations across individual teachers. They further group these different types into categories, drawing on ideas from the philosophy of science. Mcneill and Krajcik (2007) looked at the effect of teachers' instructional practices on student learning. They observed thirteen teachers transacting the same curricular material. They found that individual instructional practice varied both in terms of type and quality. This variation was reflected in student understanding of the corresponding aspects of scientific explanation. Leite, Mendoza & Borsese (2005) show that students, teachers and prospective teachers all have difficulty in making predictions or providing explanations related to the liquid state especially at the sub-microscopic level.

Lachner and Nuckles (2016) show that the quality of instructional explanations can vary with different knowledge bases that instructors have. Here explanations by mathematics teachers and mathematicians were compared and it was found that mathematicians provided the reason why a particular step in a solution was required (process orientation) whereas the teachers just provided the steps (product orientation). It was found that students who learned with process oriented explanations outperformed students who were taught with product oriented explanations. Geelan (2013) provides a video analysis of teacher explanations in the context of physics and identifies features such as the ability to move between qualitative and quantitative methods, appropriate use of analogies, requirements to succeed in high stakes exams, use of technology, and humour as important. Charamloumbus, Hill and Ball (2011) claim that the practice of providing explanations is learnable, and argue for training in providing explanations an integral part of prospective teachers' education.

Analogies have been identified as an important feature of teacher explanations. Glynn (2007, 2004) proposes the teaching with analogies model. In teaching according to this model, the teacher identifies similarities between the analog concept and the target concept. The differences are also identified and parts where the analogy breaks are discussed. Analysing the use of analogies by exemplary teachers and textbook writers, Glynn (2007) extends this idea to web-based instruction. Here they propose guidelines for designing elaborate analogies used in web-based instruction. Wong (1993) points to the generative capacity of analogies in generating new insights and inferences, in addition to fuelling conceptual understanding. Treagust et.al, (2003) identify both sub microscopic and symbolic representations in chemical explanations, and the way these play a role in the development of relational understanding in undergraduate students. They also point out the assumptions made by teachers about students' understanding of the role of representations. The use of animism and anthropomorphism in early year science teaching is attributed by teachers as a cause of cognitive problems in young children. The prevalence of such use has been also correlated to lack of content and pedagogic knowledge on the part of the teachers (Kallery, 2004). Teleological explanations can lead to alternative conceptions. While they provide explanatory reasons for the occurrence of chemical transformations (Talanquer, 2007), their use is generally correlated with the use of over generalisations.

Analogy as a feature of teacher explanations is discussed at length in the literature and dominates the discourse surrounding teacher explanations. There are other features discussed as well, but in general the theorising of teacher explanations does not align well with contemporary theories.

2.6 Research on Metaphors and Analogy in Science Education in the Indian context

In the Indian context several studies have examined the use of metaphors and analogies in classroom teaching and learning. Below we summarise some important studies

Kalra and Baveja (2012) analyse metaphors used by teachers to describe knowledge, learning, and learners. They identify recurring metaphors, such as: Knowledge as a "building" that needs construction, Learners as "vessels" to be filled with information, among others. The study highlights how these metaphors reflect teachers' underlying pedagogical beliefs and influence instructional strategies. For instance: A "building" metaphor emphasizes structured knowledge delivery. A "vessel" metaphor may encourage rote learning rather than critical thinking. It is argued that encouraging teachers to reflect on their metaphors can promote more student-centred teaching approaches. Upadhaya and Sudharshana (2021) explore how metaphor-based tasks can improve learners' understanding and use of language. Their study, situated in Indian classrooms, integrates task-based language teaching (TBLT) to foster metaphoric competence. Examples include: Tasks involving interpreting proverbs and their metaphorical meanings. Designing exercises that encourage students to relate metaphors to their social and cultural contexts. The study demonstrates how metaphors enhance creative thinking and linguistic flexibility, helping learners grasp abstract linguistic concepts. Tailored metaphor-based tasks are essential in multilingual and diverse classrooms, aiding comprehension and application of complex language structures

In addition to studies on metaphors, people have also focused on the role of analogies in science education. Kumari (2016) examines the role of analogies in making science accessible and engaging for students. By using familiar analogies, such as comparing electric circuits to water flow, teachers can simplify complex ideas while encouraging conceptual understanding. Examples include: Tree growth as a metaphor for ecosystem interdependence; Pulleys explained through analogies to simple machines in daily life. The study emphasizes that analogies not only simplify content but also stimulate curiosity and engagement, particularly in topics considered difficult, such as physics or chemistry. Teachers can use analogies to scaffold students' understanding from everyday experiences to advanced scientific concepts.

In general, metaphors and analogy as features of teacher explanations are discussed at length in the literature and dominate the discourse surrounding teacher explanations. There are other features discussed as well, but broadly the theorising of teacher explanations does not align well with contemporary theories

2.7 Unravelling Gaps in the literature

In this section we discuss how the review of different frameworks helped us identify some of the gaps in existing research. These helped us frame our research questions.

The SFL framework looks at language use in a given context. It views different features of AL including grammatical structure from a functionalist point of view. It analyses and accounts for a diversity of uses of AL in the educational context, such as student learning, teacher education etc. touching upon the issues of equity and access. It however remains a framework that deploys a macro lens to view AL and the issues surrounding it. In order to have a holistic understanding of the role of AL in education, there is a need for a framework that would provide scope for a more fine-grained analysis. This would complement the broad-based analysis of SFL well.

Cognitive linguistics seemed to be an appropriate paradigm to complement SFL. We reviewed two frameworks within Cognitive linguistics; the frameworks of conceptual metaphor and conceptual blending. Both of these frameworks address the issue of student learning, but relatively fewer studies within these frameworks take up the issue of teacher education or teacher cognition. These frameworks also do not address the problem of AL sufficiently. Conceptual blending is a framework that primarily focuses on online conceptual integration and does not really deal with AL. Conceptual metaphor as a framework focuses on comprehending abstract concepts in terms of the concrete. It theorises that the conceptual metaphor is a connection between the source domain and the target domain. It however does not explicitly deal with the problem of AL

There is a need for a framework that would not just focus on the learning of concepts, but also deal with their teaching, in active classrooms. Such a framework should be able to provide an analytical lens that would be able to differentiate between the different moves that a teacher makes in a classroom while teaching abstract concepts embedded in AL.

2.7.1 Development of the Research Questions

As discussed in the above sections, much research has been devoted to the understanding of how concepts are learned. In this thesis we are interested in understanding how teachers build abstract models in students’ minds. These abstract models are linguistically structured in a way that is very different from the learner's everyday language. We reviewed literature on AL, SFL and the cognitive linguistics frameworks of conceptual metaphor and conceptual blending, to understand how these different theoretical orientations approach the problem of the teaching of mechanism models that are embedded in AL. We have identified gaps in the reviewed literature and place our study in relation to these studies, especially the identified gaps. Keeping this in mind these gaps, we propose the following research questions

1. How do teachers restructure AL, to build new internal models of scientific mechanisms in student minds?
2. What are the cognitive mechanisms involved in this process?
3. How does AL bring into being (constitute) scientific mechanisms?
4. How can we build educational technology applications that allow teachers to systematically build mental models of scientific mechanisms in student minds?

2.7.2 Reviewing Frameworks of Cognition

As discussed, the gaps identified by reviewing the literature on AL motivated us to formulate the research questions mentioned above. The next pertinent thing with regard to our research is the adoption of an appropriate theoretical framework. In chapter 1 we mentioned our inclination to adopt a framework that integrates the role of actions, as teachers build mechanism models in students' minds partly through actions in the classroom. To facilitate this we review different frameworks of cognition in the next sections (7, 8 and 9). We discuss how the framework of the Embodied simulation theory of language (ESTL) best suits our research goals, and how this choice evolved in relation to the theoretical ecology available in literature. We start with a review of the information processing model of cognition in the next section. This is followed by the theory of embodied cognition, its extension to ESTL, and distributed cognition theory.

2.8 The Information Processing model of cognition

Behaviourism considered the mind as a black box, and focused just on observable behaviour, particularly motor actions in response to stimuli. The cognitive revolution developed as a challenge to this approach of behaviourism. Prominent thinkers (Miller, 2003) within this paradigm were interested in understanding the working of the black box. The prominence of computers as a technological advancement in that era led to the use of computers as an analogy for the mind. The comparison between the computer and the mind was inevitable, as even though they were physically different, both appeared to think. The question was what could they have in common that made it possible for them to think. The answer was both are symbol processors with some features in common. The mind was thus conceptualised as a symbol manipulating/processing system. In this physical symbol system hypothesis (PSSH), symbols were thought to have physical instantiations. They had representational properties i.e. they stood in for real things in the world. These symbols were assumed to be invariant across contexts. In this view, where symbols assumed a role of prominence, thinking was thought to be the manipulation of these symbols according to rules. The arbitrary relation of the symbol to the referent was thought to be another commonality between the computer and the human mind, as a series of zeros and ones in the computer represents the concept of a chair, creating an arbitrarily reference. Similarly, the human mental symbol for a chair refers to it in an arbitrary manner.

2.8.1 Challenge to the Information processing model

The physical symbol system hypothesis (PSSH) enjoyed considerable success for a significant amount of time; however certain gaps/problems were pointed out by subsequent theorists. These theorists challenged the arbitrariness of these symbols when modelling human cognition. The possibility of alternative models was explored, wherein symbols would have a more realistic relation with *"the structure of semantic memory"* (McClelland & Elman, 1986). Also, the notion of de-contextuality of symbols did not find much empirical support (Tulving & Thomson, 1973).

The PSSH calls for a separation between representations and the processes that act on them. In the dynamic systems perspective, representations cannot be thought of without processes. In the perception action perspective, our actions are strongly related to our perception. The PSSH does not distinguish between the human body and a computer housing the symbol manipulation system (Glenberg, 2013)

2.8.2 Mind and body distinction

The distinction between the body and the mind, separates thinking away from the body and locates it firmly in the mind. There is evidence from several studies that suggest that this is not the case. Studies in visual perception show that for the same distance, people with low energy levels or carrying heavy backpacks are more likely to feel tired. The perception of distance is thus affected by the state of the body (Proffitt, 2006). Changes in the body result in changes in cognition. As the corrugator muscle used in frowning is affected due to botox injection, people's ability to perceive anger is also reduced (Havas et.al., 2010). The body and actions don't just affect or contribute to cognition, but they play a *constitutive* role in cognition. Thinking is grounded in the sensorimotor system, and is considered to be the same as the running of a simulation of sensorimotor experiences.

2.9 Embodied cognition model

The Information processing model of the mind (Fodor, 1975) was challenged by the embodied cognition (EC) perspective that proposed a constitutive role for the body in cognition. Proponents of EC argue that our bodily structures, sensory system and motor capabilities significantly influence cognitive function (Clark, 1997). This framework argues that cognition is context dependent, i.e. it emerges from dynamic interactions with the environment. This contrasts with cognition as a static process detached from external circumstances. It challenged the conception of the brain being the sole processing unit. It also challenged the organism and environment duality. Approaches such as ecological psychology propose organism environment mutuality. The consideration of the cognising entity does not end at the skin of the organism, it encompasses the environment surrounding the organism in a dynamic way. Symbols are considered as grounded in past experiences, which challenges the arbitrary relation between a symbol and its referent. In this framework the role of representation and symbols is extensively debated. For some theorist's representations do not have any place in EC – only the dynamic interaction that organisms have with their environment exists, and cognition is fundamentally tied to action. According to the action-perception cycle proposed by Varela, Thompson and Rosch (2017), perception, cognition and action form a continuous loop. This challenges classical theories that treat perception as passive and cognition as separate from the body’s capabilities.

2.9.1 Empirical evidence for EC

2.9.1.1 Motor Resonance

One of the most compelling pieces of evidence for EC comes from studies on motor resonance. Mirror neurons, discovered in monkeys, fire not only when an individual performs an action but also when observing others performing the same action (Rizzolatti & Craighero, 2004). This provides a link between action and cognition, where understanding others actions involves simulating those actions in one's motor system.

2.9.1.2 Gesture and thought

Research on gestures supports the idea that bodily actions play a role in cognitive processes. For example, Alibali, Spencer, Knox and Kita (2011) showed that when people used gestures while explaining a concept, they perform better at problem solving tasks, suggesting that bodily movements aid cognitive functions. Goldin-Meadow’s (2003) work further supports this view, by showing that children who gesture while learning mathematical concepts tend to achieve better understanding and retention, highlighting the cognitive benefits of embodied actions.

2.9.1.3 Language and embodiment

Neuroscientific studies have shown that processing language, particularly action related verbs like *kick* or *grasp* activates motor areas in the brain. Pulvermuller et.al. (2004) found that when participants heard action related words, the corresponding motor areas of the brain became active, suggesting that understanding language involves simulating action within the motor cortex. This supports the idea that language comprehension is embodied, grounded in sensory motor experiences (Barsalou, 2008)

2.9.2 Radical position in the embodied cognition framework:

One of the more extreme positions within the embodied cognition framework is that representations are unnecessary altogether. This perspective is known as radical embodied cognition (REC) or non-representationalism (Chemero, 2009). Advocates of this view argue that cognitive systems do not need to create internal representations, because cognition arises directly from the body’s interaction with its environment.

2.9.2.1 Dynamical Systems Theory

One key model supporting the radical embodied cognition view is dynamical systems theory

(Beer, 1995). Here, cognition is modelled as a continuous, time-dependent process, where mental states emerge from the dynamic interplay between the agent and the environment. Cognitive functions are thus seen as ongoing processes, without the need for discrete, static representations.

2.9.2.2 Affordances

Another important embodied cognition concept is affordances, derived from the work of J.J. Gibson (1979). Affordances refer to the opportunities for action that the environment offers to an agent. In this view, perception is not about constructing an internal model but about directly perceiving actionable possibilities in the world. For example, when seeing a chair, we do not need an internal representation of the chair's features; instead, we perceive it in terms of its affordance—its potential to be sat on.

2.9.2.3 Situated Action

Lucy Suchman's (1987) work on situated action also critiques the reliance on internal representations. She argues that cognitive tasks are often context-dependent and improvised, relying heavily on real-world interactions rather than pre-planned, representation-based processes. In her study of human-computer interaction, Suchman showed that users often adjust their actions dynamically based on environmental feedback, challenging the idea that behaviour is primarily guided by internal representations.

2.9.3 Arguments for Representations in Embodied Cognition

Despite the radical claims of non-representationalism, many researchers within embodied cognition (EC) still see a role for representations, though representations are often conceptualised differently from classical cognitive science. Instead of amodal, abstract representations, embodied approaches tend to focus on modal, grounded, or sensorimotor representations that are tied to the body and action.

2.9.3.1 Mental simulations

One key argument for the continued relevance of representations comes from neuroscientific evidence of simulations in the brain. Studies by Barsalou (1999, 2008) suggest that when people think about actions or objects, they activate sensory-motor areas of the brain associated with those actions. This process of grounded cognition implies that cognitive representations are modal, meaning they retain traces of the sensory and motor experiences. For example, when thinking about grasping an object, people activate the motor areas of the brain involved in grasping. These representations are still internal, but they are not the amodal symbols of classical cognitive science; instead, they are sensorimotor simulations that help guide thought and action.

2.9.3.2 Hybrid Models

Some researchers propose hybrid models that integrate representations with embodied and dynamic processes. Clark and Toribio (1994) argue that while embodied cognition is useful for understanding real-time interactions with the environment, certain tasks—particularly those requiring off-line cognition (thinking in the absence of immediate sensory input)—still necessitate the use of representations. In this view, the brain may rely on minimal, action-oriented representations when interacting with the world but turn to more abstract representations for planning, reasoning, and other higher-level cognitive tasks.

2.9.3.3 Predictive Coding

Another important argument for representations comes from the predictive coding framework (Clark, 2013). This theory suggests that the brain constantly generates predictions about sensory input based on prior experience and uses these predictions to guide perception and action. These predictions are effectively representations of the expected state of the world, allowing the brain to anticipate and correct for discrepancies between its expectations and actual sensory input. Even though this framework is grounded in embodied and sensorimotor processes, it still relies on internal models or representations of the environment.

Within Embodied Cognition, a theory of reading comprehension that makes use of mental simulations – called the embodied simulation theory of language (ESTL) – conceptualises understanding as the running of a sensori-motor simulation. We discuss it in more detail below.

2.9.4 The embodied simulation theory of language:

The embodied simulation theory of language (ESTL) is a theoretical framework under development (Bergen, 2015; Pulvermuller, 2010; Glenberg & Gallese, 2012), where language is considered to embed sensorimotor elements. In this view, understanding the meaning of words and sentences, particularly related to action and dynamics, involves activating modality-specific sensorimotor representations and processes in the brain (mental simulations). Supporting this language-as-bundled-enaction approach, studies show that language can both trigger movements and embed movements (Glenberg & Kaschak, 2002; Matlock, 2004; Bergen

& Wheeler, 2010). Further, several behavioural studies support the hypothesis that actions are mentally simulated in response to language stimuli (in everyday situations). A study by Glenberg and Kaschak (2002) showed that participants were quicker in judging the direction of motion for sentences like “open the bottle” (anticlockwise rotation) if the actions they performed in parallel were compatible with those suggested in the sentence. This was found to be true even in cases where abstract transfer was involved. For instance, in sentences like “Liz told you the story” participants' responses in judging the direction embedded in the sentence was quicker if the action they did in parallel was away from the body. Similarly, Zwaan, Taylor and De Boer (2010) showed that reading of sentences implying motion in the clockwise (“He turned the key to start the car”) or anticlockwise direction were affected by the action of turning a knob in a clockwise or anticlockwise direction to reveal the next part of the story. Even in cases of fictive motion (Talmy, 1983; 2000; Matlock, 2004), studies have shown that participants exposed to story stimuli involving longer distances, rough terrains, slow travel rates etc. took longer to judge a test sentence. Apart from such behavioural studies, evidence from eye-tracking studies also indicate the involvement of simulation in language comprehension. In a study by Spivey and Geng (2001) participants were asked to look at a blank screen while they listened to a story about a spatial scene. Even though the stories were not about motion, participants were found to shift their attention to different regions on the screen, in response to the position of spatial events in the story. For instance, for events happening on the top floor of the building, participants’ attention shifted to the top of the screen. Neuroanatomical evidence grounds such mental simulation in the activation of sensorimotor neural circuits (Pulvermuller, 2010; Glenberg & Gallese, 2012). Imaging studies show that when participants process verbs (such as walk, lick, hit, etc.), motor areas related to these movements are activated (Pulvermüller & Fadiga, 2010). In the reverse direction, the progression of motor neuron disease affects the processing of verbs disproportionately, compared to the processing of nouns (Bak, & Chandran, 2012). Supporting the enactive view further, a recent study showed that a patient with a double motor cortex exhibited faster performance for action concepts than object concepts (Miranda et al., 2022).

In classroom environments, where external artefacts and representations are used to drive learning, distributed cognition as a theoretical framework would aptly account for a major element of learning. We discuss it in more detail below

2.10 Distributed Cognition

Distributed Cognition is a theoretical framework that extends the boundaries of cognition beyond the individual mind, emphasising that cognitive processes are distributed across individuals, tools, artefacts, and the environment. Developed by Edwin Hutchins in the 1990s, (Hutchins, 1995a) it challenges the traditional notion that cognition is purely an internal, brain-based activity. Instead, distributed cognition posits that cognitive tasks are often performed by systems that include multiple agents (humans), artefacts (tools, technologies), and environmental contexts working together in coordination (Hutchins, 1995a). This review will provide an in-depth exploration of distributed cognition, its core principles, empirical evidence, and its implications for various fields.

2.10.1 Core Principles of Distributed Cognition

The following sections explore some of the core principles of distributed cognition

2.10.1.1 Cognition is Socially Distributed

One of the key tenets of distributed cognition is that cognitive tasks are frequently shared between multiple individuals. In a socially distributed system, knowledge, expertise, and problem-solving responsibilities are dispersed across different people within a group or organisation. Hutchins' (2006) classic study of navigation on naval ships demonstrated that tasks such as determining a ship's position are carried out through a coordinated effort among various crew members, each with their own specific role and expertise. Cognitive work is not confined to one person's mind but is the result of collective interaction.

2.10.1.2 Cognition is Materially Distributed

Distributed cognition also emphasises that cognitive processes are often offloaded onto external artefacts or tools. Humans use technologies, symbols, and representations to aid in their cognitive tasks, such as using calculators for arithmetic or written language for memory and communication. Norman (1993) introduced the idea of cognitive artefacts, which are tools specifically designed to enhance cognitive performance. For example, a pilot’s checklist is a cognitive artefact that externalises memory, ensuring that critical tasks are not overlooked. The external environment, including physical objects and tools, plays a crucial role in the overall cognitive system.

2.10.1.3 Cognition is Distributed Over Time

In addition to being distributed socially and materially, cognition is often distributed temporally. Actions performed at one moment can influence future cognitive tasks. This principle is evident in the use of notations and records, such as written logs, which store information for future use. Cognition is therefore not only distributed across agents and artefacts but also across time, allowing for the accumulation of knowledge and learning. In Hutchins' (1995a) research on navigation, navigators rely on past records of the ship's course and previous interactions with tools to determine future actions.

2.10.1.4 Coordination as a Cognitive Activity

Distributed cognition places significant emphasis on coordination as a cognitive process. Whether through verbal communication, shared attention, or the use of shared artefacts, coordination mechanisms allow the different components of a cognitive system to work together. Cognition is thus seen as an emergent property of the interactions between people, tools, and the environment. In group problem-solving situations, for example, coordination is necessary to ensure that each participant contributes to the overall cognitive task in a way that complements others' contributions (Hollan, Hutchins, & Kirsh, 2000).

2.11 Conclusion

The literature review played a crucial role in shaping the research questions and helped in the selection of the Embodied Simulation Theory of Language (ESTL) as the framework to address these questions.

2.11.1 Identifying the Research Questions

The review of various cognitive and linguistic frameworks, including Systemic Functional Linguistics (SFL) and Cognitive Linguistics (focusing on Conceptual Metaphor and Conceptual Blending), highlighted the limitations of existing theories in addressing the process by which teachers use academic language (AL) to build internal models in students' minds. While these frameworks offered valuable insights into the structure and use of AL, they did not sufficiently explain how teachers facilitate the internalisation of complex, abstract models through linguistic restructuring. This gap motivated the formulation of the research questions. These questions emerged from the recognition that existing frameworks lacked a focus on the dynamic, embodied processes that underlie language comprehension.

2.11.2 Embodied Simulation Theory of Language (ESTL)

The literature review led to the adoption of ESTL as the theoretical framework to address the research questions. ESTL, which conceptualises understanding as the result of sensorimotor simulations, aligns well with the research focus on how language activates mental models. This framework was chosen because it integrates findings from neuroscientific studies showing that understanding action-related language involves activating motor areas in the brain. ESTL supports the idea that language comprehension, especially in science education, is grounded in sensorimotor experiences, making it suitable for exploring how teachers use language to build complex models in students' minds.

Chapter 3: Methodology

In this Chapter

We present the method of non-participant-observation based case-study as an appropriate approach to investigate the way mechanism models embedded in AL are transformed and made available to the students through teacher narratives. We extend the theoretical construct developed in study 1 to the discipline of physics in study 2. In study 2 we also make use of semi structured interviews, to understand student comprehension of physics models and the process of modelling. For this, we make use of an interactive system developed by us to help learners build physics models. In the third study, we investigate the effect of change in language structure on the distribution of student attention, using a controlled experiment. The empirical data collection across the three studies consisted of interviews, observations, field-notes, and controlled experiments. The qualitative data from different sources were analysed using methods of thematic analysis. The analytical framework built on Embodied Simulation Theory of Language (ESTL) and Distributed cognition theory,

3.1 Introduction

The research reported in this thesis broadly aims to explore the complex interconnections between language, actions, and related semiotic resources, which together allow teacher narratives to advance student learning of mechanism models. Much attention has been paid to classroom learning from the learners' perspective, but very little work exists on characterising learning from teachers' perspective. To address this gap, we specifically focus on how teachers build mechanism models in learners' minds. We first consider the mechanism model of photosynthesis from the discipline of biology. Teacher narratives are highly dynamic, as they are contingent upon many factors, including the classroom context and student feedback. The diverse experiences that students bring to the classroom, the teacher's own understanding of the topic, her views on the nature of science, and her beliefs about teaching, along with the school's larger philosophy of education, are among the factors that contribute to the kind of approach a teacher employs in constructing explanations, and the corresponding teaching narratives. As the research questions explore different dimensions of this problem, this thesis makes use of case study as a general approach. For the first two studies, different methods are adopted at the micro level, to address specific issues related to each study. The third study explores a very focused question, so it is addressed using a controlled experiment.

Since we scoped our study to explore the teaching and learning of mechanism models, in the first study we focus on the mechanism of photosynthesis. In order to understand the role of the teacher, we observed classroom sessions where the teacher dealt with this topic. We employed non-participant classroom observation to study the case of how aspects of the photosynthesis mechanism were taught. This case was studied across at least two classroom contexts and teachers. The analysis of this data led us to propose the theoretical construct of performative bundles. In the second study, we extend this construct to a different disciplinary domain, physics. To explore the role of teacher narratives in helping students understand physics mechanisms and their building, we designed an interactive system, as a way to present a new approach to teach the building of the mechanism model. This interactive system had elements of the teacher narrative embedded in it by design.

The context of the second study differs from the first study, along the following dimensions:

- **Disciplinary context:** Each discipline has its own register; a form of disciplinary AL. The nature of objects and knowledge in physics differs from biology and necessitates the use of different representational structures and language.
- **Technological context:** In the first study, the context was technology-deficient, as the textbook formed the primary resource for comprehension. The teachers had to build the mechanism model in students' minds primarily through their explanations. In the case explored in the second study, the teacher narrative was distributed – across the interactive system developed to teach the building of the physics mechanism models, and the teacher narrative while students interacted with this system.
- **The pedagogical context:** The explanations in study 1 were provided in a lecture-based manner, while in study 2, the teacher explanations are task specific, helping students navigate through the system, and responding to the needs of the student in building the

mechanism model.

In the first study, classroom observation formed the main source of data whereas in the second study, the interview and cognitive tasks formed the main sources of data. The other important aspect of this thesis, other than the teaching of mechanism models, is the representation of the models in a specialised form of language, termed AL. It has been pointed out that the understanding of the mechanism model is often obfuscated due to the specialised form of AL that students encounter for the first time. The third study explores this aspect of the mechanism model, in the biology context. In this study, we make use of a standard experimental task called the Navon task. Through this study we explore the role of AL in modulating learners' attention during reading comprehension. Taken together, these three studies provide a richer account of the teaching and learning of mechanism models.

3.2 Research methods to understand teacher explanation - A brief review

Teacher explanations have been studied from different methodological stances. Many studies have focused on characterising the different aspects of teacher explanations (Thiele & Treagust, 1994; Lachner and Nuckles, 2016; McNeill & Krajcik, 2008). The use of analogies in teacher explanations has been a subject of particular interest (Gray & Holyoak, 2021). Irrespective of the diverse methods employed to study teacher explanations, the observation of classroom teaching learning sessions forms a major source of data. To analyse the explanations, they have to be observed in action in their contexts of generation. They can then be analysed, characterised and categorised depending on their features. They can also be studied to understand distinctive features across diverse pedagogical regimes. Certain features get illuminated when they are superimposed against the gradient of novice (pre-service) to expert (in-service) teachers. Teacher explanations can also be studied from the perspective of student learning, specifically to understand what features of teachers' explanations support certain kinds of student learning. The observation of classroom sessions thus leads to diverse methodological choices, from which the researcher selects some, depending on the aims of their research.

Dagher, Z & Cossman, G (1992) observe classes to create a typology of teacher explanations.

The authors do not define what an explanation is before observing the classes – the notion of explanation and its types emerges from the data. The method can thus be considered as a case study, as the authors observe several classes with an explicit aim of understanding explanations. They use the constant comparative method (Glaser & Strauss, 2017) in analysing transcripts generated through classroom observation. Another example of a case study approach is McNeill & Krajcik (2008), who observed enactment of the same project-based chemistry unit by 13 teachers, with 1197 seventh grade students. Here the aim was to note the diversity in the use of predefined instructional practices and the effect they have on student learning. Leite, Mendoza & Borsese (2007) compared the explanations of preservice teachers with inservice teachers, about the liquid-state phenomenon across three countries in Europe. They employed the technique of questionnaire as they were working with a large sample size. The questions used were close ended, hence the answers could be compared against the expected canonical answer. Both qualitative and quantitative analysis was used to assess the correctness of the answers and check for patterns if any emerge from this data. Lachner and Nuckles (2016) conducted an experimental study to understand the difference in mathematics teachers' (low CK and high PCK) explanation and mathematicians' (high CK and low PCK) explanation on student learning. They quantitatively analysed the data on student learning, revealing that the process approach of the mathematician's explanation was better understood by students than the product approach of the teacher's explanation. Geelan (2013) conducted a video analysis of the explanations of 16 physics teachers. Grounded theory approach was used in the analysis of the data. The generation of themes was an iterative process until the themes sufficiently captured the different features of teacher explanations. The emergent themes identified features of teacher explanations that contributed to student success in high stakes exams. Treagust, Chittleborough & Mamiala (2010) explored the role of sub-microscopic and symbolic representations in chemical explanations. This research made use of classroom observations and student and teacher interviews as sources of data. They concluded that students' relational understanding could be improved by linking behaviour of chemicals at different representational levels. Hoffenberg & Saxton (2015) undertook a case study of teacher practice, to elucidate its features that support students' explanation construction as prescribed by curricular standards. In an exploratory study Kallery & Psillos (2004) studied teachers' own views on the use of animism and anthropomorphism in early year explanations. They made use of interviews and task analysis data to arrive at their conclusions, specifically that teachers consider the use of animism and anthropomorphism in early science explanations as causing misconceptions in students, and this approach reflected a lack of content knowledge on the part of the teacher. Though the tools used here were interviews and task analysis, it can be considered a case study of a particular type of explanation. In general, across the different studies, teacher explanations are delineated as a case and studied in further detail as a case study. These insights helped us select research methods for our studies, the rationale of which is discussed in the next section.

3.3 Answering the Research Questions - Rationale for selection of research methods

Mechanism models form an important part of teaching and learning, especially in biology classrooms. Characterising the teacher's role in the learning of these mechanism models, as is the focus of this thesis, would require the observation of this process as it happens. Many of the studies reviewed in section 2 above also make use of classroom observations. The mechanism model of photosynthesis is the specific focus of our attention (discussed in section 4.1.1).

As seen in the section 2 above, the study of teacher explanations is approached through different methodological perspectives, but explanations are considered as a particular "case" to be studied. The literature suggests that case study is a method of choice in studying teacher explanations. For our study, a rich characterisation of the interaction during the teaching of the mechanism model (the specifically delineated object of study)would require observations from various vantage points. One would be to look at the explanation of the mechanism model from the perspective of the explanation provided in the textbook. Another would be to view this process in the classroom as a non-participant observer. In order to overcome the effects of a particular discipline in reading the outcome of the analysis it would also be useful to provide a comparative case from a different mechanism model in a different discipline.

We adopted the case study method for the following reasons.

- The teaching of the mechanism models is a clearly delineated process, and thus qualify as a case
- It has well defined boundaries, but at the same time it is integrated in the larger school science context

The following subsections provide further details about the case study approach.

3.4 Case study

The evolution of the case study as a methodology has seen multiple transitions. It was a frequently employed method in the social sciences post 1900 until around 1935. With the rise of quantitative techniques, questions were raised about its validity and general efficacy as a methodology. This resulted in a sharp decline in its use in comparison to quantitative methods. Interest was renewed in the 1960s, as researchers became increasingly concerned about the limitations of quantitative methods (Tellis, 1997).

Case studies have been used extensively in recent times, particularly in the context of medical and legal education. Even business education has employed case studies as a pedagogical tool. The Harvard case studies are specifically designed, and used by various institutes as well as organisations, as a tool to understand the rich dynamics and complexities of different social phenomena. Case studies are broadly classified into exploratory, explanatory and descriptive. Each of these can be a single case or multiple case type. Multiple cases here would follow a replication design and not a sampling design. Case study as a methodology also draws from diverse philosophical traditions. Some scholars lean towards a positivistic conceptualisation (Yin, 2003) of a case study, while others have a more constructivist view (Stake 1995 & Merriam 1998). This distinction has implications for different aspects of a case study. Questions such as what constitutes a case, requirements for validity, are also answered differently under these different philosophical orientations. We subscribe to the view propagated by Merriam (1998) as she strikes a balance between the relatively extreme positions adopted by Yin (2003) and Stake (1995). In this view a case study is

"an intensive, holistic description and analysis of a bounded phenomenon such as a program, an institution, a person, a process, or a social unit"

Case study as a methodological domain makes use of an eclectic mix of tools for collecting data (Yazan, 2015). The data collection tools can be qualitative such as participant and non-participant observations, interviews, surveys etc. or they can be quantitative such as experiments. Below we discuss the object of focus in a case study; the case.

3.4.1 What is a Case?

Out of the diverse methodological orientations that come under the gamut of case study, one thing remains common; the case. Some consider a case as clearly delineated from its surroundings, while for others a case is an integral part of the context.

Yin (2003) defines the case as

“a contemporary phenomenon within its real-life context, especially when the boundaries between a phenomenon and context are not clear and the researcher has little control over the phenomenon and context”.

Merriam does not distinguish between the process and object nature of a phenomena in defining a case. She defines “the case as a phenomenon of some sort occurring in a bounded context” (Merriam, 1998). It is flexible enough to include any phenomena where the researcher is able to draw a boundary around this phenomenon of interest. It presents a much wider conceptualisation of a case and case study research in general. We subscribe to Merriam’s conceptualisation of case study research for the purpose of this thesis.

3.4.2 Analysis in a case study

Researchers differ in their approach to analysing data depending on their philosophical stances. Some favour the development of first Impressions through the data in an iterative process of data collection and analysis. This follows from the epistemic stance that there is no single reality. However, there are other approaches which prioritise the objectiveness of reality and recommend strict protocols for data collection and analysis.

Case studies seek to provide a holistic understanding of the various interrelated activities that actors are engaged in a given context (Stake, 1995). One of the criticisms of case study as a methodology has consistently been: its dependence on a single case for drawing inferences. This criticism also foregrounds the concerns about its generalisability. The results from case studies contribute to theory and not directly to populations. Thus, replication in the design of case studies contributes to the robustness of the theory (Hamel, 1993).

Considering these factors, we decided to adopt the case study approach for our research. Other methods were employed within the ambit of case studies, and Covid impacted some of those choices, as discussed in the following section.

3.5 Covid and its impact on data collection

Covid played a major role in the decisions on implementing the three studies. As schools were closed for a period of about two years during the crucial data collection phase, a radical alteration in the methodological plan was necessitated. After the collection of the initial data set before Covid, attempts were made to observe online classes, but it was soon evident that the shift from offline to online classes was a many layered one. Adapting to the technology was a major challenge for both teachers and students. Several other factors, such as mental and emotional distress, weighed on the classroom interactions (Robinson, 2023; Rehman, 2021) The classrooms were very chaotic and highly challenging – in terms of management – for the teachers. It was decided that such classrooms would not truly represent the learning we intended to observe and analyse through the studies. Hence classes were not observed in the online mode.

While online classes didn’t seem to be appropriate for certain sites and forms of data collection, it proved to be a useful mode for certain other forms of data. Conducting content and task specific interviews of students at the post-graduation level, as done in study 2, proved to be well suited for the online mode. The experimental study too was done in an online mode. For such studies the online mode could be considered as compromising on rigour, as the test environment sometimes cannot be under the researcher’s complete control. Many of these issues can be resolved with careful planning. Also, the online mode provided more flexibility in student recruitment and implementation of the study.

The pandemic proved to be a major hurdle in the implementation of the study but with the advent and penetration of technologies to cope with it, it later on provided opportunities of data collection in non-conventional ways.

3.6 Scoping the study to observe only mechanism models

Mechanism models form an integral part of the school biology curriculum. Many of the modern discoveries in biology have been mechanisms. The generalised definition of mechanisms for a phenomenon (Craver & Tabery, 2019) considers both the organisation as well as the interaction of entities, such that they produce the phenomena. Using this generalised definition, mechanisms can be found in many disciplines other than biology. For the purpose of this thesis, we choose to focus on mechanism models and models of mechanisms across the disciplines of biology and physics.

3.7 Summary of the research methods

Following is a summary of the research methodology employed across the three studies. A detailed description of the methodology used, including data collection and analysis for each of the studies described below is available in Chapter 4 (Study 1), Chapter 5 (Study 2) and Chapter 6 (Study 3).

3.7.1 Overview of study1: The teaching of biology mechanism models

The study explored how teaching narratives help students build mental models of scientific mechanisms in biology. The core objective was to understand how these models are constructed in students' minds through narratives, using mechanism terms (MTs) for subsequent recall and activation. This study's broad research question focused on how teachers restructure academic language to build these models, with a specific emphasis on teaching photosynthesis.

We employed the case study methodology, making use of classroom observations. Three case studies were chosen from observed teaching sessions in biology classrooms. These sessions were recorded and analysed to identify how teachers bring about the building of these models in students' minds. The analysis followed a structured three-step approach:

1. **Data Transcription and Identification**: The audio recordings from teaching sessions on photosynthesis were transcribed, and relevant teaching episodes were identified.
2. **Characterising the interactive dynamics of the episode**: Episodes were analysed from the standpoint of the teacher, particularly focusing on the enactive strategies they employed while teaching.
3. **Generation of a generalised mechanism model**: This part of the analysis focused on how observations and analysis from the previous steps can be extended to form a more generalised mechanism model of this process

The study observed 10 teaching sessions by four biology teachers (T1–T4), covering both grades 7 and 10, and teaching various topics, such as photosynthesis, reproduction in plants, and cellular biology. Out of these, three sessions focusing on photosynthesis (by T1 and T2) were selected for detailed analysis.

The teachers came from two different government schools: one followed the Central Board for Secondary Education (CBSE) curriculum, and the other followed the Maharashtra State Board curriculum. These two educational contexts were chosen to examine how teaching narratives work across different curricular frameworks.

Data collection involved **audio recording** of the classroom sessions, as video recording permissions were not granted. Two audio recorders were placed in the classroom (one at the front and one at the back) to ensure comprehensive capture of the teaching sessions. In addition, detailed field notes were taken by the researchers, who were non-participant observers during all sessions.

The focus was on biology teaching, particularly sessions involving the topic of photosynthesis, which has been identified in previous research as a conceptually challenging topic for both students and teachers. The choice of this topic was also supported by its nature, as it is part of an interconnected network of mechanism models in biology.

The analysis process was driven by two perspectives:

1. **Teacher Cognition Perspective**: This approach examined how teachers constructed their teaching narratives to deal with the cognitive challenges of explaining complex mechanisms like photosynthesis. This included how teachers simplified or expanded on textbook descriptions, to make the content more accessible to students.
2. **Cognitive Mechanism Perspective**: This analysis focused on how students were able to understand and manipulate the internal models of the biological mechanisms that were taught. Mechanism-building episodes from the classroom were analysed for how they helped students move from sensorimotor experiences to the academic terms and formal models used in biology. The teachers' use of narratives was examined to understand how they "loaded" technical terms with sensorimotor imagery, helping students internalise complex processes.

Further validation of the analysis was done through triangulation with a physics dataset, though this part is not included in the current results.

3.7.2 Study 2: Physics derivation study

This study employed a mixed methods approach, combining qualitative and quantitative data collection and analysis.

The study used a 5-step model of deriving equations, which was developed based on a review of physics textbooks. This model was implemented in an interactive system designed to help teachers develop new model-building narratives. This system was then tested with a group of 10 physics students, primarily graduate students, who were asked to complete a variety of tasks both before and after using the interactive system.

Data was collected through a combination of:

- Pre- and post- intervention interviews: Questions were asked about the student's understanding of derivations and equations, and about how the system helped their understanding.
- Performance on a series of tasks: These included an open-ended problem-solving task, an ordering task, a labelling task, and an equation-description task.

The interview data was transcribed and analysed using a method called conceptual blending, where the researchers looked for instances of the student connecting two or more concepts, and scored these instances as high, medium, or low on the strength of the connection. The performance data was also analysed, with the researcher scoring the student's performance on each task as high, medium, or low. The researchers were careful to note how each student was able to understand the different elements of the 5-step model and how this connected to their performance on the other tasks.

3.7.3 Study 3: Connection between language structure and mental simulation through attention

The study investigated the effects of linguistic restructuring on attentional states, specifically looking at how nominalization in scientific texts (academic language, AL) influences attention. Participants were divided into two groups, one reading a textbook passage (control condition) and the other reading a modified passage (experimental condition) where nominalization was reduced and passive voice was converted to active voice. Both groups were then asked to complete a Navon letter task, both before and after reading the passages, to measure their attentional biases.

The results suggest that nominalization in AL can influence attention. The participants who read the control passages (with nominalization) tended to focus on local features of the Navon task, while those who read the modified passages tended to focus on global features.

This study employed a mixed repeated measures design, with a 2 (between subject factor: nature of passage- textbook, modified) X 2 (within subject factor: target letter type-local, global) X 2 (within subject factor: test sessions- pretest, post-test) factorial structure. 35 Participants (18 female and 17 male) were randomly assigned to either the textbook passage (non-modified, control condition) or the modified passage (experimental condition). All testing was conducted in-person, in a single session, on a 15.6-inch LED HP laptop screen. Both task stimuli and task sequence were pilot-tested with a sample of ten 9th grade students before they were implemented in the study. Consent was provided by all participating students before the experiment. Each student was exposed to 14 Navon task trials in the pre and post-tests. The pre and post-tests contained 7 local and 7 global trails, randomly assigned.

The study used the Navon letter task as a probe, to examine whether reading these passages led to any systematic changes in attention. We calculated the mean Global-Local RT bias (GLB) for each student. If participants respond faster to the local trials, they have a local bias. If they respond faster to global trials, they have a global bias. GLB is the difference between the mean global reaction times (GT) and the mean local reaction time (LT), across trials.

Chapter 4: The role of teachers in connecting student simulation with AL

In this Chapter

Mechanism models are an important part of school science curriculum. These models are abstract and often require extensive teacher support in the form of explanations, especially in contexts where access to technology is limited. We analyse teacher explanations of mechanism models related to photosynthesis using the theoretical framework of enactive cognition. The analysis is done in three stages; firstly, we compare the teacher narrative to the corresponding textbook narrative. Secondly, we present an interactive summary of the explanation episode, including the different enactive strategies used by the teacher. Thirdly we present an abstract view of the episode outlining the different phases in which the episode progresses, and also provide the simultaneous progression of the explanation being built using enactive elements. All the three episodes analysed here differ from each other, reflecting the variability of content and the expected level of complexity of explanations according to the grade level and the strategies used in constructing them. Integrating these case studies and analysis, we propose the theoretical construct of the performative bundle (PB), as a general model of the teaching of mechanisms. The PB model considers teachers as carefully seeding the abstract mechanism models using students' everyday experiences, and connecting these experiences to the content of the mechanism model being discussed. This chapter is based on ***Salve, J., Upadhyay, P., Mashood, K. K., & Chandrasekharan, S. (2024). Performative Bundles: How Teaching Narratives and Academic Language Build Mental Models of Mechanisms. Science & Education, 1-39.***

4.1 Introduction

4.1.1 Teacher explanations: A ubiquitous aspect of classroom interaction

After the advent of constructivism, the critique of lecture-based methods has relegated explanations given by instructors to a lower level in the value hierarchy of classroom pedagogy. But irrespective of the pedagogy used, explanations form a cardinal element of any form of teaching, in diverse contexts (Mcneill and Krajcik, 2007). In developing country contexts – where the number of students in a classroom is high and access to technology is limited – most classrooms function in lecture-based mode. Teachers explain the content in the text, which is considered to be inaccessible to students on their own. The lectures attempt to create a bridge between the known and the unknown, primarily through the means of language. It is among the few resources available to the teacher in such contexts. The abstract concepts are embedded in an academic language structure (this is generally the case with most science concepts), making the concepts inaccessible and alienating to students. Irrespective of the context, explanations are important tools for the teacher to drive learning. Even in contexts where knowledge construction happens through student-led interactions, where teachers act as mere facilitators, they often guide student construction of explanations, or engage in narratives and practices that help students construct explanations (Mcneill and Krajcik 2008; McNeill, Lizotte & Krajcik, 2004). The quality of explanations may differ from teacher to teacher, depending on different factors, such as the experience of the teacher or the disciplinary context etc., but they remain an important aspect of classroom interactions irrespective of the pedagogical approach used.

In this study, we look at classrooms following the traditional lecture-based pedagogy. The challenge that the teacher faces in the classroom in such a scenario is twofold. She has to

1) Construct an explanation of the abstract conceptual networks presented in the textbook, and
2) Help the students gain fluency in the disciplinary AL.

For this, she has to foreground the conceptual structure embedded within the AL structure of the textbook. This necessitates the unravelling of the dense conceptual structure as presented in the textbook, in ways that students can be expected to understand. The teacher does this by connecting the abstract concept with the pre-existing conceptual structure that has emerged from (is abstracted from) the daily life experiences of the students, or memory traces that the students may have of these experiences. The teacher negotiates a dual challenge; she makes the abstract mechanism model in the textbook comprehensible to the students, but at the same time she also builds up the AL structure of the textbook in which the concepts are embedded. For this, she deconstructs the dense conceptual structures by connecting them to everyday life experiences and then reconstructs the AL structure back again, but in a way that the mechanism terms now become comprehensible.

This chapter characterises this process, which is common across science classrooms. The context here is the analysis of classroom episodes related to photosynthesis, an important mechanism model of school biology. We adopt an enactive cognition perspective as our analytical lens, where understanding is viewed as the running of a sensorimotor simulation. For the simulation to run successfully, the dense conceptual networks are mapped onto existing sensorimotor experiences of the student. The teacher, while unravelling these dense conceptual networks, maps them onto their sensorimotor experiences, in the process animating the static textbook description. In the following section we introduce what we mean by mechanism, drawing on related literature in the philosophy of science.

4.1.2 Mechanisms and their learning

Formally, mechanisms are a specific class of scientific explanations, studied mostly in the philosophy of biology and philosophy of science (Glennan, 2017; Machamer et al., 2000). Apart from biology, mechanism-based explanations are also developed in other natural science disciplines like physics and engineering. To capture the role of mechanism-building in science and engineering, philosophical concepts related to mechanisms—such as nomological machines (Cartwright, 1997), the machinic grip (Pickering, 2010), and representational machines (Chandrasekharan & Nersessian, 2021)—have been developed in the philosophy of physics and philosophy of engineering. The philosophical literature on mechanisms is quite complex and spread across multiple domains. A deep dive into these detailed discussions would take us far from our objective of developing an account to support teacher education. Since such an exhaustive review is also not necessary for our purposes, we will be working with the following two consensus definitions of mechanism (Craver, & Tabery, 2019) in this chapter:

> *A mechanism for a phenomenon consists of entities and activities organised in such a way that they are responsible for the phenomenon. (Illari & Williamson, 2012)*

> *A mechanism for a phenomenon consists of entities (or parts) whose activities and interactions are organised in such a way that they produce the phenomenon. (Glennan, 2017)*

Note that these definitions consider the mechanism as a specific way of characterising a phenomenon in the world. Drawing on these definitions, and the wider philosophical discussion on mechanisms, the main aspects of mechanisms we focus on here are as follows:

- Their part-whole (componential) structure
- Their activity (dynamic) nature
- Their "bundling" into mechanism terms and other external representations (ERs; Kirsh, 2010)

In our view, for learners to understand a mechanism, they need to interlink these three aspects (components, dynamics, ERs) into a cohesive network. We consider the term "mechanism concept" as referring to this integrated network. In this paper, we use the term "mechanism model," instead of "mechanism concept," as we analyse the nature and learning of the first two properties of the network (componential nature, dynamics) as a model, and examine separately how these are encapsulated within formal symbolic systems ("bundling" of mechanisms into formal terms and ERs).

4.1.3 The Building of Internal Mechanism Models

The building of internal (mental) mechanism models, as well as their understanding and processing, has been studied in cognitive science, particularly using the case of gears (Schwartz & Black, 1999; Hegarty, 2004). This literature indicates that complex mental simulation ("running" and manipulation of internal memory structures, particularly sensorimotor structures), such as mental rotation of chemical structures and frames of reference, is the dominant cognitive process involved in the understanding and processing of mechanisms. Based on the central role played by mental simulation, this cognitive process has been used to develop theoretical accounts of both scientific discovery (Clement, 1994; Nersessian, 2010) and science learning (Clement, 2003; Clement et al., 2005; Landriscina, 2015). Within cognitive science, mental simulation, which can be thought of as "virtual" action, is proposed by action-based ("enactive") theories and models of cognition, which seek to ground higher-order cognition processes in action and sensorimotor activity[1].

[1]

Examples include the activation of sensorimotor areas during mental rotation (Schwartz & Holton, 2000; Wexler et al., 1998; Wohlschlager, 2001), and the use of sensorimotor forward models to predict inanimate movements, such as ocean waves (Schubotz, 2007). Importantly, the studies reviewed above focus on the cognitive processes involved in mechanism understanding. They do not explore the key pedagogical and developmental question we examine here: how are new mechanism models built in learners' minds, through interaction with standard external representations (ERs) and teaching narratives?

This question could possibly be addressed using a distributed cognition (DC) framework, as the key operational elements here—external representations and teacher narratives— are outside the mind (thus distributed), and they together help generate internal models. However, the nature of the distribution of cognition here is different from the standard cases examined by classical studies—such as landing an aircraft (Hutchins, 1995b) and navigating a ship (Hutchins, 1995a)—where the analysis focuses on the way mental work during a complex task is "offloaded" to external representations and structures. In contrast to this inside-to-outside "divergent" model of DC, the building of mechanism models in student minds requires an outside-to-inside "convergent" model of DC, where focused internal mental models and networks are generated through a complex intertwining of external structures, such as ERs and teaching narratives. This type of DC is not well understood, and is also less well studied (but

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[1] *For clarity, we distinguish between theories that emphasise action-based ("enactive") and body-based ("embodied") models of (4E) cognition, even though these approaches are closely related, as they both appeal to body-centred processes. By enactive cognition theory, we refer to work in the neo-Jamesian ideomotor tradition (Hommel et al, 2001), where the dominant theoretical concepts are sensorimotor resonance, forward models, sensorimotor simulations, and extension of the body schema through tool use. The analysis here focuses on actions and associated neural systems, and the formal modelling approach used is control theory. By embodied cognition theory, we refer to work in the neo-Gibsonian (Cutting, 1982) ecological psychology tradition, where the dominant theoretical concepts are affordances, ecological information, optic flow, and the whole organism. The analysis here focuses on the body, and the formal modelling approach used is dynamic systems theory. A key difference between the two approaches is that the ideomotor (enactive) approaches seek to reform—and therefore work with—classical cognitive psychology constructs such as memory, internal representations, and neural correlates of states of the world and the self. Recent radical threads in the ecological (embodied) approach (Chemero, 2009; Di Paolo et al. 2017) reject these classical constructs. We follow a more middle and pragmatic path, where we use the neo-ideomotor model when seeking to account for higher-order cognition and learning, as these processes, in our view, are better understood as involving memory, imagination, and interaction of internal and external representations. Specifically, we consider these processes to be based on manipulation of stored internal traces of embodied actions. However, these traces, in our view, are stored using highly dynamic systems, such as networks of neuronal and cellular processes (e.g., place cells and grid cells).*

see Rahaman et al., 2018; Martin & Schwartz, 2005). The work reported here thus also contributes back to basic research, by extending the convergent aspect of distributed cognition theory.

4.2 Methodology

In this study, we examine the way teaching narratives help learners build and manipulate new internal mechanism models in biology. We also examine the way mechanisms are bundled into mechanism terms (MTs), which allow the activation of the generated mechanism models later in student minds, in highly specific ways. Based on the above overall structure, we seek to address the first research question in this study,

1. *How do teachers restructure AL, to build new internal models of scientific mechanisms in student minds?*

which includes the following sub-question

How are new internal mechanism models and their mechanism terms (MTs) built in student minds through teaching narratives?

These questions are very broad and have significant theoretical and application implications. Addressing them systematically requires an extensive and longitudinal research program. Here, we report a preliminary study in this direction, where the key objective is to develop a systematic theoretical and empirical approach to address the above questions. We first present three illustrative cases of mechanism-building in a biology classroom and develop a three-step analysis of the role of teacher narratives in this generative process.

The three case studies we use to develop our theoretical account are based on two audio datasets and related field notes.

4.2.1 Sample

Overall, 10 sessions of 4 teachers of grade 7 and 10 teaching various topics were observed (Please refer to the table given below). For the photosynthesis study, three teaching sessions of two biology teachers (T1 and T2), teaching the mechanisms of photosynthesis (in grades 7 and 10), were observed (two grade 7, one grade 10) and audio recorded. All classes were conducted in a lecture-based manner. These data are presented as part of this study.

Teacher	Grade	Topic	Board	Classes observed
T1	10	Photosynthesis	CBSE	1
	7			1
T2	7	Photosynthesis	State	1
	7	Cell		3
T3	10	Reproduction in Plants	CBSE	2
T4	7	Cell	State	2

Table 4.1 Classes on different topics that were observed as part of the study
The ones highlighted in red were used for analysis.

4.2.1.1 Students

The classroom observations were carried out at two different government school systems. The students from the state board school belonged to lower socio-economic strata, many of them are first generation learners. Parents of a few students had completed school education. The classroom was linguistically diverse with Hindi, Marathi, Tamil and Urdu being spoken as their first language. The classroom also varied with respect to academic achievement and reading levels with some students clearly struggling to read from the textbook while some others could read up to their grade level.

The students from the CBSE board school belonged to lower to middle socio-economic strata. Some of the students in this classroom were first generation learners but many of the students had educated parents who had either completed school or college education. The classroom here too was linguistically diverse with Hindi, Marathi, Tamil, Bengali etc, being spoken as the first language. Here a majority of the students could read from the textbook when prompted by the teacher.

4.2.2 Data Collection

The observations were done at two different government school systems (across two different school boards). One school followed the Central Board for Secondary Education curriculum whereas the second one followed the Maharashtra State board curriculum. Prior permission was taken from the school authorities and teachers to attend and audio record classes. Video recording of the classroom sessions would have been ideal but permissions for the same were not forthcoming and it was thus decided to go ahead with the audio recordings. Oral consent was taken from the students. The researchers were non-participant observers during all the teaching sessions. The classes were audio recorded, and notes were taken in parallel by the researchers. Two audio recorders (one at the front and the other at the back of the classroom) were used.

4.2.3 The choice of photosynthesis as a topic

Several studies have pointed out that students find the learning of photosynthesis challenging (Canal, 1999; Barker and Carr, 1989; Métioui et.al., 2016), with many conceptual difficulties, at different stages in school education (Marmaroti & Galanopoulou, 2006; Södervik et.al., 2015). Teachers too find the teaching of photosynthesis conceptually challenging (Krall et.al., 2009). Our choice of photosynthesis as a topic for our research is based on these conceptual challenges. Apart from these, we also consider photosynthesis illustrative of the nature of biology, as it acts as a network, interconnecting many mechanism models contained within it. It also connects to other networks, with mechanism models of their own, such as respiration in plants. Even models at the ecological scale, such as energy flow, biomass, plant animal interaction, sudden transitions in ecosystems etc. are related to the photosynthesis network.

4.3 Analysis

Audio data from the observed teaching sessions was transcribed and some relevant teaching episodes and common themes were identified. These episodes and themes, as well as the textbook descriptions of the mechanism that the teacher was teaching, were then analysed from two perspectives:

1. A ‘teacher cognition’ perspective, where all the episodes and themes were examined from the standpoint of the teacher, and the cognitive problems she was facing and solving.

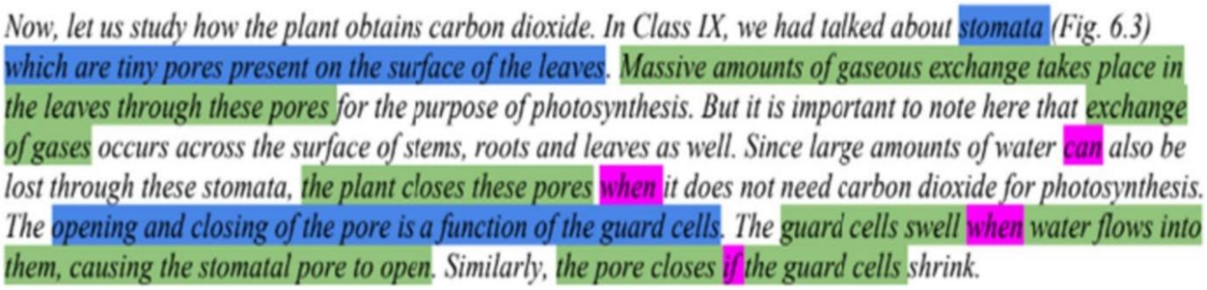
2. A cognitive mechanism perspective, where all the episodes and themes were examined from the standpoint of the cognitive processes involved in: a) student understanding of the biological machinery under discussion and b) the building of the teacher narratives of the biological mechanisms.

The constructs derived from these analyses were then triangulated using another dataset, where the team analysed video data of two physics instructors guiding a cohort of students towards an understanding of atmospheric pressure, using an experiment-based interaction (based on a barometer) and related discussions. This analysis is ongoing, and thus not presented here. But given the similarities we found—despite the different topic (physics) and teaching format (collaborative and inquiry-based pedagogy)—this analysis provided an initial reliability test of our approach and also allowed us to widen and generalise the theoretical model presented here.

To illustrate the building of an internal model of a mechanism through a teaching narrative, we first present a brief structural analysis of a passage (see Fig 4.1) on photosynthesis. This passage (on transpiration) is drawn from a grade 10 textbook from the CBSE board. We then present a teaching episode, where the teacher helps students "enact" the transpiration mechanism, by extending their own sensorimotor experiences. She also helps students "load" these sensorimotor experiences into new technical terms, by systematically using technical terms in association with the extended sensorimotor experiences created by teaching narratives. The passage is edited for clarity.

The photosynthesis mechanism is extremely complex, and this passage only deals with one relatively simple component of it (transpiration). As learning advances, students are required to progressively build on, and mentally manipulate, this mechanism model. The transpiration model is based on imperceptible components (such as guard cells), whose activity and state changes (dynamics), and relation to other elements (such as water, heat, and gases), are central to understanding the transpiration mechanism. Transpiration thus provides a good illustrative case of mechanisms, with part-whole structure and dynamics that vary with inputs, as well as the dynamic activity changing the whole structure.

As indicated in Fig. 1, textbook descriptions of mechanisms capture these components and their complex dynamics, in specific formal terms, generating a standardised, but quite dense, academic language (Schleppegrell, 2001; Snow & Uccelli, 2009). To learn science, students need to internalise this dense academic language structure, as it allows learners to mentally activate, apply, and manipulate the intricate mechanism models in nuanced ways and in novel situations, such as labs and exams. Teaching narratives provide critical transition pathways for students to internalise this new language structure, by providing many different support structures that allow learners to gradually transition from their everyday language to academic language.



Now, let us study how the plant obtains carbon dioxide. In Class IX, we had talked about stomata (Fig. 6.3) which are tiny pores present on the surface of the leaves. Massive amounts of gaseous exchange takes place in the leaves through these pores for the purpose of photosynthesis. But it is important to note here that exchange of gases occurs across the surface of stems, roots and leaves as well. Since large amounts of water can also be lost through these stomata, the plant closes these pores when it does not need carbon dioxide for photosynthesis. The opening and closing of the pore is a function of the guard cells. The guard cells swell when water flows into them, causing the stomatal pore to open. Similarly, the pore closes if the guard cells shrink.

Figure 4.1: Analysis of Textbook Passage.

The blue text indicates the creation of new concepts, through definitions, and also the encapsulation of these definitions under new terms. Later use of the term, in a different context, would require the student to regenerate the mental process generated by the definition—for instance, to understand the way the defined entity behaves in a new context. The green text shows embedded dynamics (state changes and transformations). The pink text shows mechanisms with possible conditional (can, when, if) branches. These branches embed two possible scenarios at the same time. One of these scenarios is "empty," in the sense that it is indicated, but not explicitly discussed. This "latent meaning" structure makes such conditional sentences quite dense, and difficult for learners to process, as the alternate scenario also needs to be considered, in an implicit way

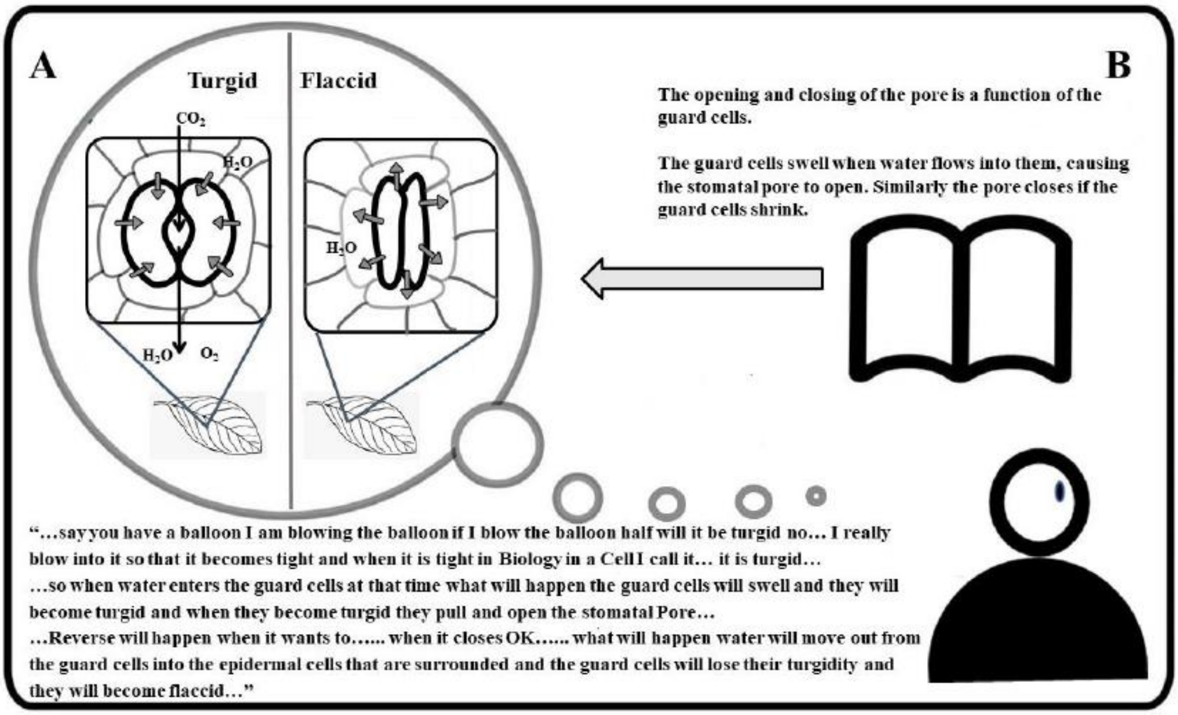
In a developing country classroom context like ours, students mostly have access only to textbooks and the formal descriptions, terms and diagrams present in it. We focus our analysis here on such text-centric, resource-limited, and teacher-driven learning contexts. In more resource-rich contexts—where teachers and students might have access to other representational resources like interactive simulations, animations, and physical models—the details of this analysis would be different. However, while the teaching aids and external representational resources used by teachers to build their narratives would be different in resource-rich contexts, teachers need to build narratives in such classrooms as well. This requirement for narratives suggests that our analysis would be applicable even in such contexts.

Since understanding the mechanisms, as presented by the textbook, requires mentally simulating their imperceptible dynamics in the right way, science teaching focuses on helping students reconfigure their existing sensorimotor experiences, to generate the new structures and their dynamics correctly. By reconfiguration, we mean the process by which teachers systematically change students' existing sensorimotor experiences, towards novel, nuanced, and specific dynamic imagery and mental simulations, which replicate the target dynamic mechanisms in students' minds. As teachers use new technical terms systematically in association with this reconfiguration process, they also help students "load" (Redish & Kuo, 2015) these reconfigured sensorimotor processes (mental simulations) into the formal terms. The reconfiguration process thus embeds enactive simulations — and thus meaning—into formal terms, figures, and embodied states (such as gestures, and body-based anchors like the Fleming's Left Hand Rule in electromagnetism). The reconfiguration process also allows students to understand, mentally manipulate, and build on mechanisms.

This proposal—where mental simulations are embedded into technical terms through association—is different from Redish and Kuo's (2015) proposal of "loading," where mathematical terms in physics are considered loaded (embedded) with physical reality. However, both mental simulation and association are involved in the physics case as well, though these cognitive processes are not examined in detail in existing accounts. We illustrate the reconfiguration and loading processes below, using a teaching episode related to transpiration.

4.3.1 Case 1

In this example, the teacher is trying to explain the mechanism of the opening and closing of the stomata during transpiration. For this, the teacher makes use of the analogy of a balloon, which grounds this imperceptible phenomenon, and its associated technical terms, using a sensorimotor experience familiar to students. Note that the structure of this sensorimotor experience is only *similar* to the structure and dynamics to the opening and closing of stomata. It does not provide a fully accurate mapping to the mechanism. It is used to start a 'seed' mental simulation, which reorganises existing sensorimotor experiences in a specific way. This reorganised structure provides a stable simulation, which can then be revised systematically, to generate a closer mapping to the textbook description of the mechanism.



The opening and closing of the pore is a function of the guard cells.

The guard cells swell when water flows into them, causing the stomatal pore to open. Similarly the pore closes if the guard cells shrink.

"…say you have a balloon I am blowing the balloon if I blow the balloon half will it be turgid no… I really blow into it so that it becomes tight and when it is tight in Biology in a Cell I call it… it is turgid…
…so when water enters the guard cells at that time what will happen the guard cells will swell and they will become turgid and when they become turgid they pull and open the stomatal Pore…
…Reverse will happen when it wants to…… when it closes OK…… what will happen water will move out from the guard cells into the epidermal cells that are surrounded and the guard cells will lose their turgidity and they will become flaccid…"

Figure 4.2: A schematic representation of the teacher's explanation of the transpiration process.

The teacher narrative (part A) is presented alongside the textbook narrative (part B). The dynamic process of the opening and closing of the stomata in the teacher narrative maps the structure and dynamics of the mechanism, as given in the textbook narrative. This mapping is done by expanding and enacting the textbook narrative, making the mechanism dynamics action-based, and "loading" technical terms like "turgid" and "flaccid" with mental simulations—all using the action-based narrative

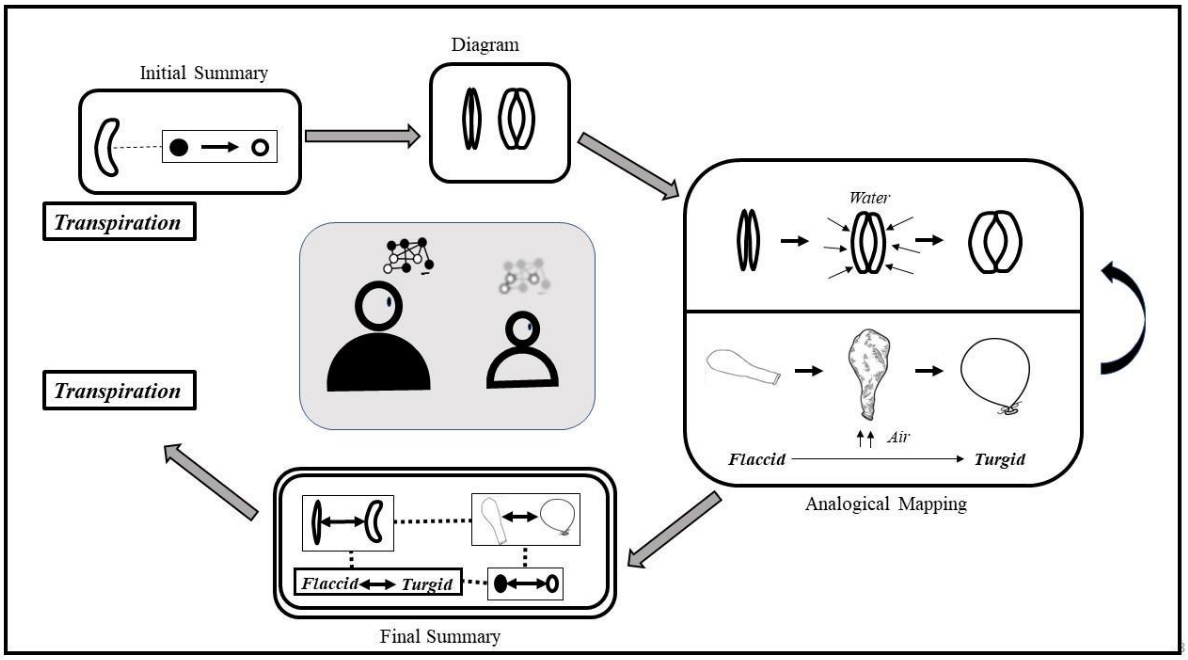


Figure 4.3: A structural analysis of the transpiration teaching episode.

It depicts the teacher's use of several enactive moves, to build a mental simulation of the imperceptible transpiration process in students' minds. This includes the initial use of summaries and diagrams (top left panels), gestures, analogical mappings (right panel), and final summary (bottom left panel). These components together build internal models of the imperceptible mechanisms, by drawing on learners' existing sensorimotor experiences. This process refines the student's initial gist simulation of the mechanism model (hazy network in the middle panel), moving it closer to the canonical mechanism model (the teacher's sharper network in the middle panel)

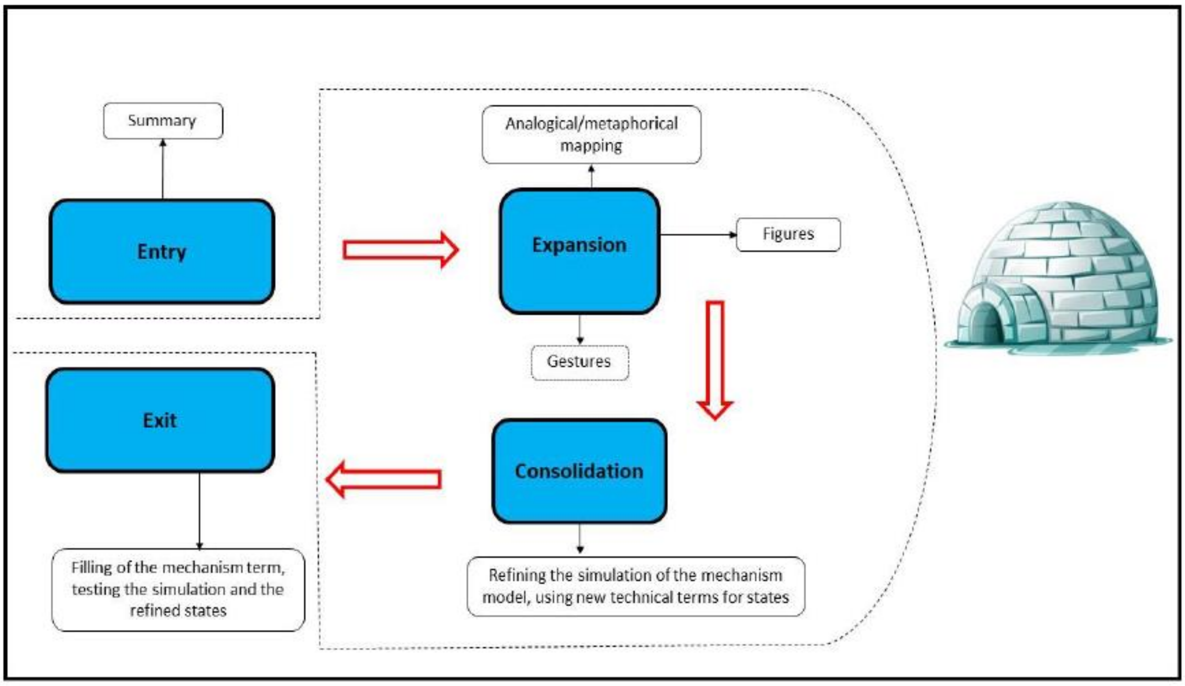


Figure 4.4: The Igloo Model for the transpiration case.

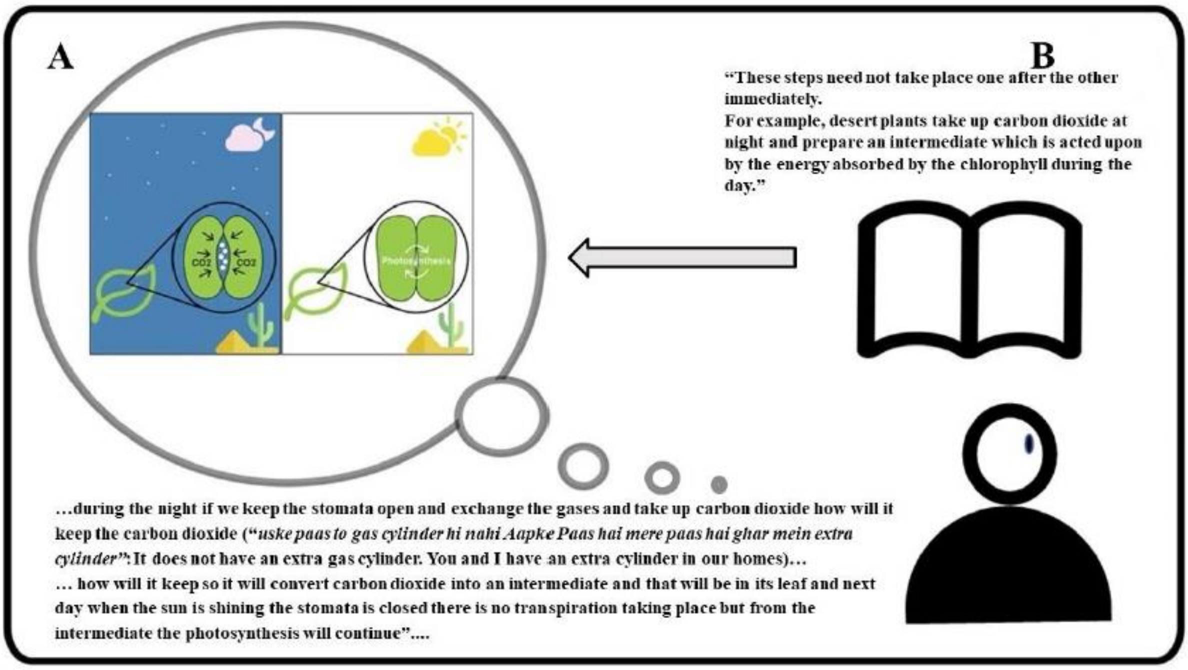
How teachers build mental simulations of scientific mechanisms in students' minds, and "load" these simulations into technical terms, for later activation. This figure presents a schematic general model of the way a mechanism model is built. This schema idealises the earlier figure, capturing the teacher's explanation of the transpiration process as a general pattern, abstracting out the different phases in a teacher's model-building. The teaching narrative starts with the entry into the model-building episode, using an initial summary. The teacher then expands on this summary, using several enactive strategies to extend and remap learners' existing sensorimotor experiences, thus generating the new mechanism model. This is followed by a consolidation phase, where the initial summary is modified, to include the refined understanding generated in the expansion, and also some new technical terms. During this process, the teacher also links the refined mental simulation of the mechanism to the top-level technical term. Later encounters with the term can now activate the mechanism model, as well as its specific states. The teaching episode then exits, with an evaluation, particularly by testing the stability of the new states and associated terms that have been added to student simulations of the mechanism. In terms of overall structure, this process—of generating the internal mechanism model, and encapsulating the model and its parts into technical terms—resembles an igloo

The teacher also introduces novel words like *turgid* and *flaccid*, which are more precise than terms like 'tight' and 'loose', in the context of the balloon example. As the balloon is compared to the cell, the conceptual schema for turgidity is exemplified well. The elasticity of both the cell and balloon membrane make it possible for them to expand on filling. The material filled in the cell is water, while the balloon is usually filled with air. The experience of the growing tightness of the balloon connects to the turgidity of the cell.

The mapping is not perfect, and it is deployed as an overall template to build an initial understanding of the dynamics of the imperceptible mechanism. The balloon is mapped only to the guard cell, and not to the entire assemblage, which includes a pair of guard cells in a specific spatial configuration. The teacher makes drawings on the board while she is mapping the two structures. She draws the guard cell and the stomata, and indicates the exchange of gases using arrows. This drawing extends the mapping, by inviting the learner to consider the two guard cells as balloons. It also maps the changing shape of the balloon to the changes in the guard cells. The teacher's enaction of the mechanism using gestures and drawing further consolidates the understanding of the changes in the mechanism components, and its associated flow dynamics. Note that the teacher *reconfigures* the balloon experience, to develop the detailed structure of the guard cell. This process requires the student to revise her internal simulation of the balloon significantly, to track the mapping the teacher is setting up.

4.3.2 Case 2

In this case, the teacher develops a second mechanism model. The teaching narrative here is centred around a trade-off—between keeping the stomata open to take in CO_2, and the simultaneous loss of water in the form of vapour. She presents the importance of this trade-off using the context of desert and similar environmental conditions, where water is scarce. To ground this trade-off, the teacher builds on a concrete sensorimotor experience familiar to students (the use of a cooking gas cylinder). This example grounds both the abstract biological problem (use of intermediate chemicals by plants, to address the above trade-off) and a technical term related to photosynthesis ("intermediate"). The cooking gas cylinder, a common feature in most developing country households, is used by the teacher to map the storage of CO_2 in a stable form, termed an intermediate.



"These steps need not take place one after the other immediately.
For example, desert plants take up carbon dioxide at night and prepare an intermediate which is acted upon by the energy absorbed by the chlorophyll during the day."

…during the night if we keep the stomata open and exchange the gases and take up carbon dioxide how will it keep the carbon dioxide (*"uske paas to gas cylinder hi nahi Aapke Paas hai mere paas hai ghar mein extra cylinder"*: It does not have an extra gas cylinder. You and I have an extra cylinder in our homes)…
… how will it keep so it will convert carbon dioxide into an intermediate and that will be in its leaf and next day when the sun is shining the stomata is closed there is no transpiration taking place but from the intermediate the photosynthesis will continue"….

Figure 4.5: A schematic representation of a teaching episode where the teacher helps students simulate the process involved in the mechanism of storing CO2 using an 'intermediate'.

This mechanism is seen in some desert plants. The teacher narrative (part A) is presented alongside the textbook narrative (part B). The teacher's narrative builds on the textbook narrative, by expanding it using a concrete experience students share (the use of a cooking gas cylinder at home). This experience-based narrative reconfigures the textbook description of the problem the plant is solving, by remapping it using action terms.

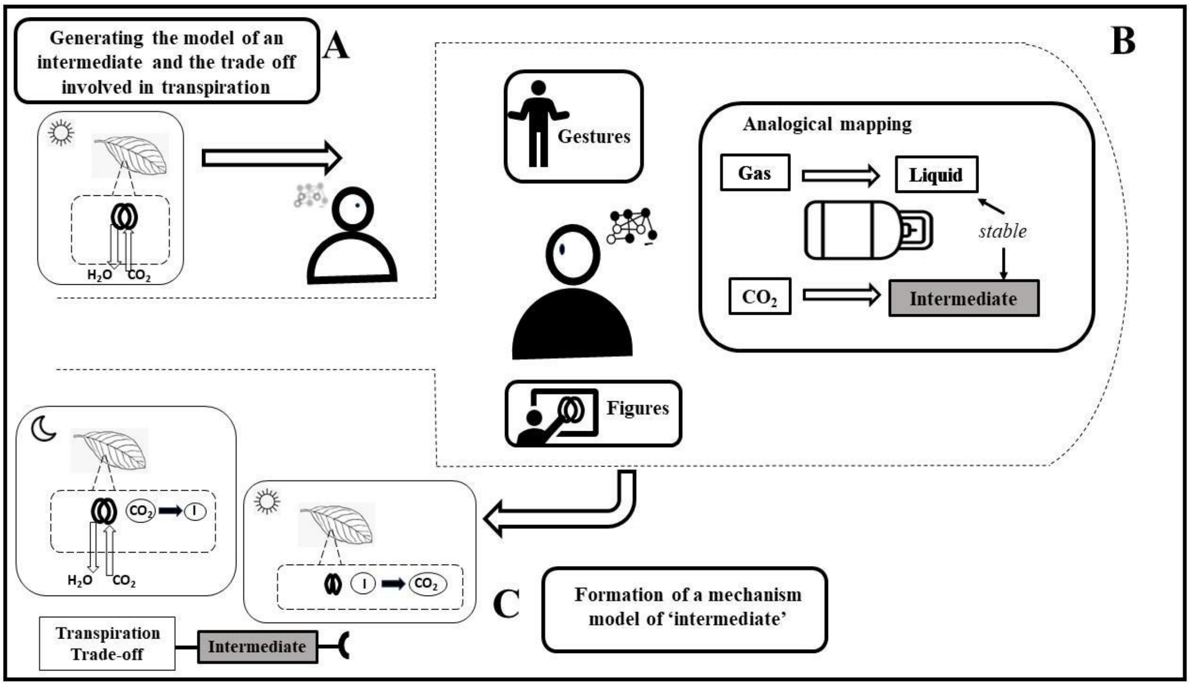


Figure 4.6: A schematic representation of a teacher's simulation for the term 'intermediate', and also the trade-off involved in transpiration, using the conversion of CO2 into an intermediate in some plants

In Part A, the teacher presents the problem of the transpiration trade off (evaporation if the guard cells are open during the day) to the student. In Part B she expands on the problem, using several enactive strategies like gestures, figures, and analogical mapping. She uses the analogy of a cooking gas cylinder, which allows the student to access the sensorimotor experience of cooking using the stored gas in a cooking gas cylinder. The idea of the intermediate mechanism is mapped to the idea of stored cooking gas in the cylinder. This cylinder structure creates an analogical map to the storage function and stability of the intermediate. In Part C, the technical term 'intermediate' is presented, as a general solution to the trade-off problem. This term, with the loaded sensorimotor experience, can now act as a stable node, which can be connected to other nodes in higher classes, to construct the complex conceptual network of photosynthesis.

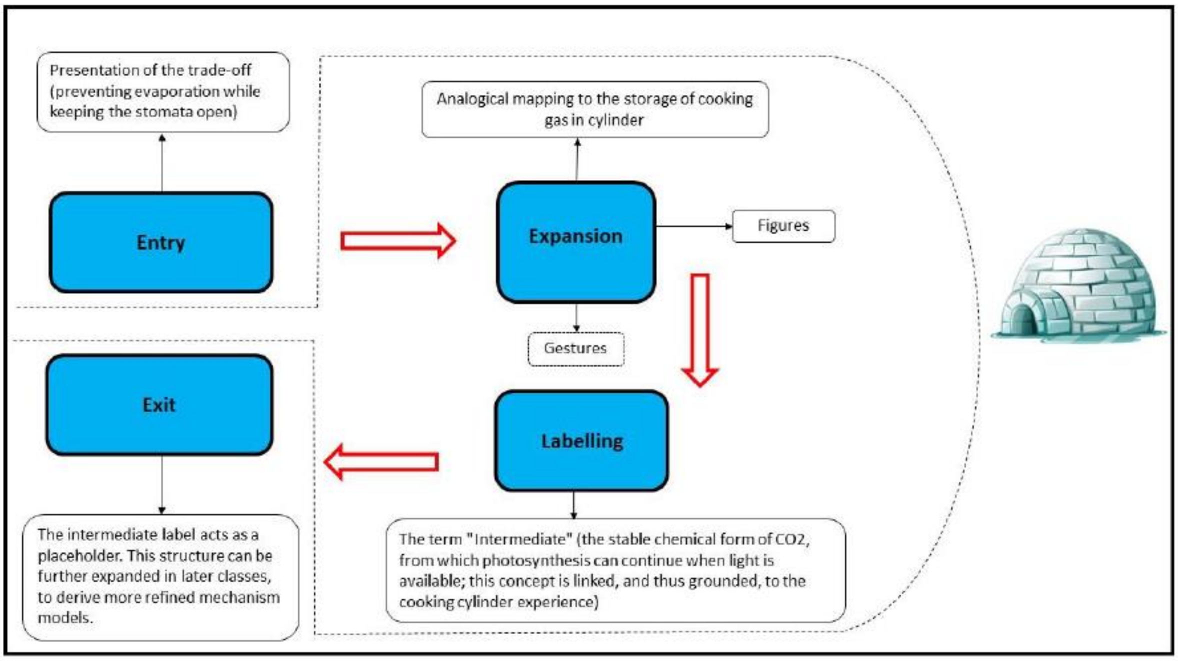


Figure 4.7: The Igloo model for the episode involving the formation of the intermediate.

The schematic general model of building the internal model of the 'intermediate' mechanism, idealising from the previous figure, which captures the teacher's explanation of the formation of an intermediate in photosynthesis. The idealised model focuses on the different phases in a teacher's model-building, starting with the entry into the model-building episode, using a problem situation (the trade-off involved avoiding evaporation while keeping the stomata open). The teacher then expands on this problem, using several enactive strategies to extend and remap learners' existing sensorimotor experiences, thus seeding a new mechanism model. This process is followed by a labelling phase, where the 'intermediate' is proposed as an important node in the mechanism model. The technical term 'intermediate' is loaded with the enactive simulations developed in the expansion phase. The term can now be used to later activate these actions. The term 'intermediate' acts as a placeholder, and can be expanded in later classes, by adding more details, generating a more refined mechanism model. The teaching episode then exits with an evaluation, particularly by testing the new states that have *been added. Structurally, this process of generating the internal mechanism model using analogical mapping, and encapsulating the model and its parts into a new technical term, resembles an igloo.*

As discussed in case 1, the analogical mapping here is not perfect, but it gets a minimal mental simulation going for students. In the current case, the storage of the gas in the cylinder shares certain properties with the storage of CO_2 in the form of an intermediate, but the analogy breaks in other aspects[2].

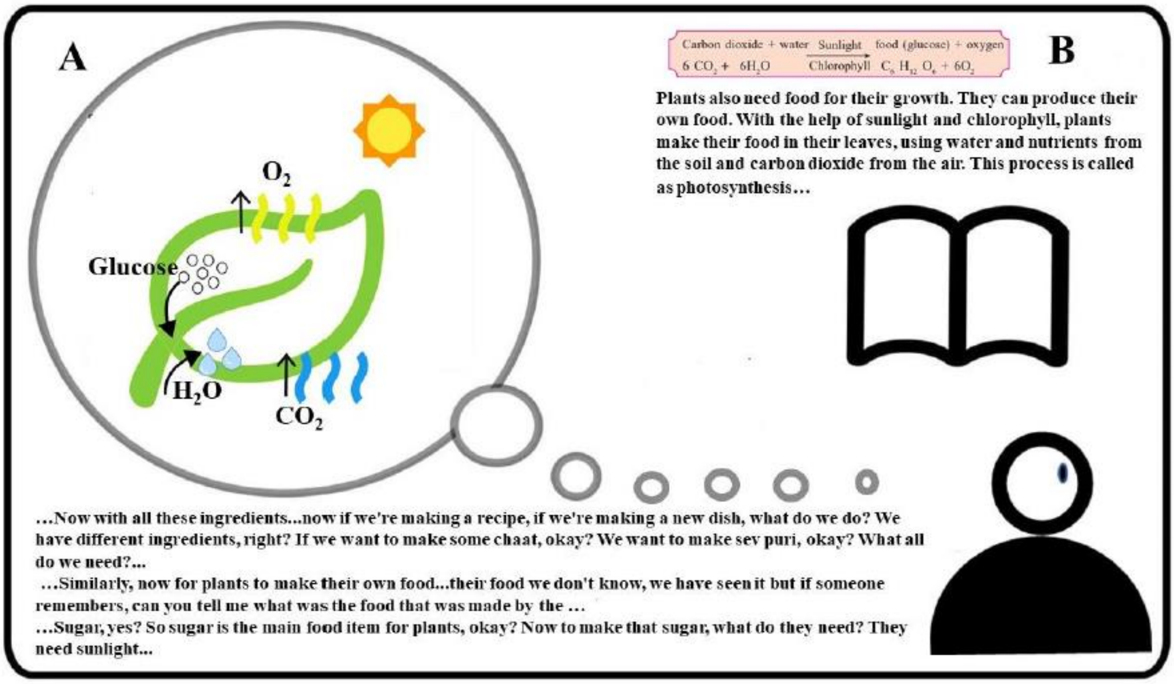
Labelling the stable chemical that is temporarily stored as an "intermediate" is a very significant pedagogic move, as it allows the teacher to deftly control the complexity of the mechanism network that she is building. Specifically, this labelling helps the teacher to restrict the complexity of the student simulations, foregrounding the process of the formation of the intermediate (which is stable) from the formation of CO_2 (an unstable form). This restriction and management of complexity is informed by the teacher's knowledge of the way the photosynthesis mechanism develops detailed structure as the topic advances in the curriculum. In this case, she is aware that the intermediate node in the current (grade 10) mechanism network will be reopened further (in grade 11), as a small network of its own. We illustrate this case using Figs. 4.5, 4.6, and 4.7. These figures are sequenced similarly to the above case (initial description of the textbook and teacher narratives, detailed analysis of the way the teacher's narrative builds the internal model, idealised general schematic (igloo model) of the teacher narrative).

4.3.3 Case 3

In this case, the teacher develops "seed" models for two very new concepts, which students have never encountered before (chemical reaction, chemical equation). The teacher first uses a concrete, but approximate, sensorimotor experience (the making of a popular snack, by mixing ingredients) to ground the abstract idea of a chemical reaction.

She then "loads" this understanding into a formal technical representation (the equation for the chemical reaction). Since grade 7 students have not encountered a chemical equation before it appears in this particular case, the teacher faces a rather difficult challenge— building a mental simulation in the students' mind for two totally new, interrelated, and also foundational, concepts.

[2]



$$\text{Carbon dioxide} + \text{water} \xrightarrow[\text{Chlorophyll}]{\text{Sunlight}} \text{food (glucose)} + \text{oxygen}$$

$$6\,CO_2 + 6H_2O \xrightarrow[\text{Chlorophyll}]{\text{Sunlight}} C_6H_{12}O_6 + 6O_2$$

Plants also need food for their growth. They can produce their own food. With the help of sunlight and chlorophyll, plants make their food in their leaves, using water and nutrients from the soil and carbon dioxide from the air. This process is called as photosynthesis…

…Now with all these ingredients...now if we're making a recipe, if we're making a new dish, what do we do? We have different ingredients, right? If we want to make some chaat, okay? We want to make sev puri, okay? What all do we need?...

…Similarly, now for plants to make their own food...their food we don't know, we have seen it but if someone remembers, can you tell me what was the food that was made by the …

…Sugar, yes? So sugar is the main food item for plants, okay? Now to make that sugar, what do they need? They need sunlight...

Figure 4.8: A schematic representation of the teacher's explanation of how plants 'prepare' food.

The teacher narrative (part A) is presented alongside the textbook narrative (part B). In the teacher's narrative, there is a dynamic process – the chemical reaction of reactant molecules under certain conditions to give oxygen and food (glucose) as the products – which maps structurally and dynamically to the textbook narrative. The teacher narrative expands on this textbook description, especially the chemical equation, which the students are encountering for the first time. She expands on the reactants to products conversion more specifically the addition part of the reactants, and maps it back to the technical terms used such as Glucose, Carbon dioxide etc.

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[2] *For instance, the CO2 is converted to an intermediate and stored in the vacuoles. It is later made available for fixation through the Calvin cycle. In the analogy, the vacuoles map to the external encasing of the gas cylinder, whereas the "intermediate" is analogous to the stable liquid form (LPG). When required for cooking, this stable liquid form gets converted to the gaseous form, analogous to the conversion of the intermediate into CO2. This process however differs in certain aspects to the LPG case, such as in the relative positions of the vacuoles and the cell in comparison to the cylinder and the gas stove. The analogy thus works only until the release of CO2, but the information about where it is released is not part of the analogy. The gas cylinder being connected to the gas stove does not represent well the connection between the vacuole and the cell.*

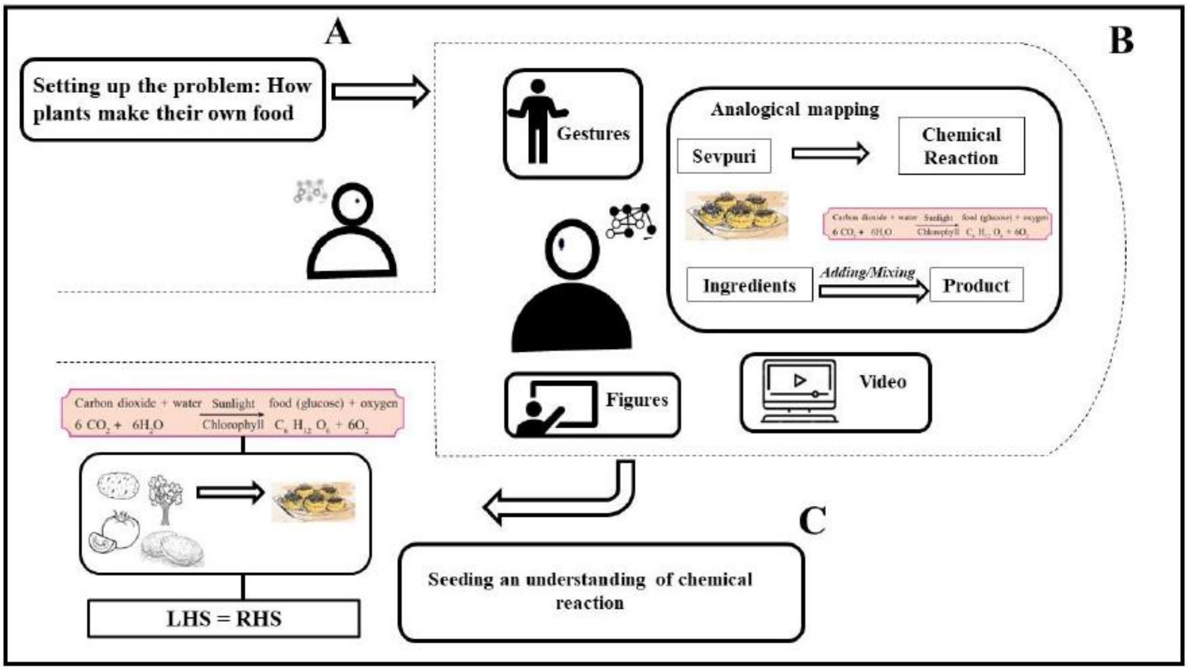

Figure 4.9: Case 3: The photosynthesis chemical equation. An interactional summary of the way the teaching episode progresses.

This figure shows the way the teacher builds the concepts of a chemical reaction and its equation, while discussing photosynthesis with students. This is the first time grade 7 students are encountering a chemical equation. The teacher thus needs to 'seed' a new mental model to get a gist simulation of reactions, and also the concept of an equation, up and running. In part A, the teacher sets out the problem. Part B illustrates the different components of the teacher's explanation. The teacher makes use of an analogy – sev puri (a popular snack, created by mixing many ingredients) – along with gestures, figures, and an animation video, to create a mental model of the way plants 'prepare food'. She 'seeds' the gist simulation for a reaction, using the analogy of mixing of ingredients to create sev puri. This structure is then mapped to reactions, particularly the way reactants are combined to generate a product. The sev puri analogy to the chemical reaction (which the teacher highlights as approximate) is then consolidated, by connecting it to a technical term – the formal chemical equation. This external representation (the chemical equation) also seeds the idea of equality of the left-hand side and the right hand side in a mathematical equation, its relation to conservation (and possibly also the idea of equilibrium)

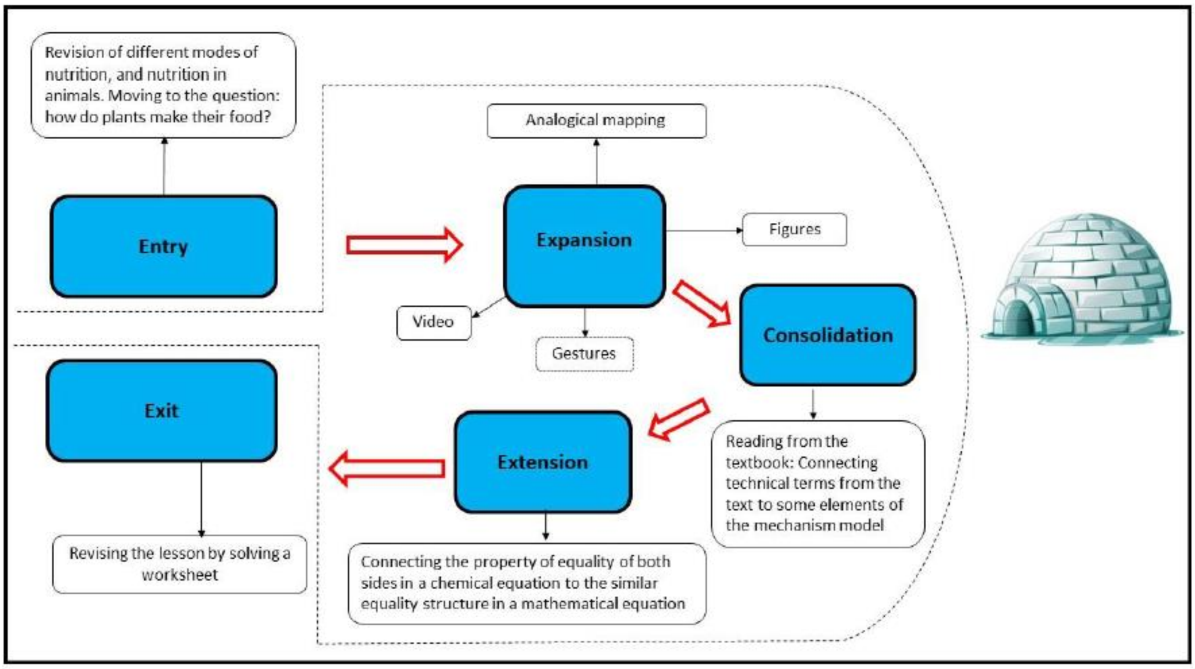

Figure 4.10: The Igloo model for case 3: A schematic general model of building a mechanism model,

Drawing on the previous figure, which captures the way the teacher builds a seed model of food preparation in plants. This idealised model focuses on the different phases in the teacher's model-building, starting with the entry into the model-building episode – by gradually transitioning from animal nutrition to the question of how plants make their food. The teacher then expands on this discussion, using several enactive strategies to extend and reconfigure learners' existing sensorimotor experiences, to generate the new mechanism model. This phase is followed by a consolidation phase, where the teacher asks the students to read the textbook. Here the refined understanding generated in the expansion phase is connected to the technical terms students encounter in the textbook. These terms can now activate the expanded mechanism model – and its states – during later encounters. This phase is followed by an extension phase, where the teacher extends the chemical equation representation, to connect it with the representation of a mathematical equation. This extension is done to seed some of the other properties of a chemical equation – such as the equality of number of molecules on both sides. The teaching episode then exits with a worksheet solving activity, which tests the new model that has been added, and its states.

Building an understanding of what these symbols stand for, what it means to combine them, and that too under certain conditions, is a difficult task when the students have very little in terms of a network for the teacher to build on. To address this issue, the teacher makes a decision—to focus on only certain parts of the network. She focuses on reactants combining to form products, but for simplicity, she "mutates" (Kahneman & Miller, 1986) this process into a kind of mixing, to give students an initial grasp of the process. Simplistically, the mixing process can be thought of as the adding together of some entities, to give rise to a combined form of those entities. To get this basic simulation going, the teacher uses the analogical mapping of preparing a popular snack, by mixing different ingredients. The different ingredients map to the different molecules involved in the chemical equation. The act of mixing these ingredients to get the desired snack is mapped to the addition of these reactants to form a product. Note that this analogical mapping focuses only on the aspect of adding components together. Given the minimal network structure that students come with, this mapping only gives learners a basic sense of the process, and not the detailed sense of the relations between the structural aspects of the components. Specifically, the molecules in the equation and the mixed ingredients do not share structural properties. The mapping is thus very broad and general. Nevertheless, it contributes a minimal brick to the incremental process of building the mechanism network in student minds.

After setting up this analogy, the teacher then consolidates this relatively simple network through textbook reading, revisiting the nodes and their connections, and sometimes

adding more connections. To move this rudimentary network closer to the equation network, she discusses certain similarities between the chemical equation and mathematical equations (which students are familiar with). In the mathematical equation, the LHS is equal to the RHS. Similarly, in a chemical equation, the reactant side and the product side must be equal, in terms of the number of contributing elements. This analogy, between the chemical equation and mathematical equation, allows the teacher to set up a minimal simulation for the new concept—of a chemical equation.

We illustrate this case using the set of Figs. 4.8, 4.9, and 4.10. These figures are sequenced similarly to the first and second cases (initial description of the textbook and teacher narratives, detailed analysis of the way the teacher's narrative builds the internal model, idealised general schematic of the teacher narrative).

4.3.4 Reliability study

To examine the reliability of our analysis, we presented the above case studies and the figures to three teacher participants (two males and one female, all had more than 2 years of teaching experience) and asked them whether they agreed with our analysis and its graphical representation. This was followed by a discussion on their reasons for agreement/disagreement.

All participants agreed with the analysis, but had extra comments, mostly on the figures. Participant 1 (3 years teaching experience) felt that the analogies were interesting, but said that these were likely to create misconceptions. Interestingly, one comment was “the entry, expansion, and exit capture most classes…about what a teacher does.” The participant felt the figures could be improved. Participant 2 (3 years teaching experience) commented that the circular nature of the igloo model could be confusing, so it would be better to have a linear model. It was suggested that the flow in Figs. 1 and 2 for each episode could be changed, mainly to present the analogies first and then the concepts (for instance, balloon first and then guard cell). Participant 3 (teacher educator, 2 years of teaching experience) felt that there was a clear mapping between the words in the transcript and the figures. It was suggested that Fig. 1 could be linear, as the circular structure is “weird.” For Fig. 2, it was suggested that the structure could be triangular, instead of circular.

This brief study does not fully ensure the inter-rater reliability of our analysis. However, it does provide indicative evidence that the analysis is robust.

4.4 Performative Bundling: Science Teaching as Building of Mental Models of Mechanism

The above three cases present specific examples of how teacher narratives help learners build an internal mental model of a mechanism, and associate it, as well as its states, to specific technical terms. To develop a general account of this operational process of building mechanism models, we extend two cognitive theories: the enactive simulation theory of language, and distributed cognition. Briefly, the former considers language understanding to involve mental simulation. However, this theoretical account is currently based on empirical studies of the way verbs and stand-alone sentences are processed. This basic model needs to be extended and scaled significantly to account for mechanism cases such as transpiration, particularly to include the processing of whole textbook passages and technical terms, and teaching narratives. The model we present here offers an approach to move to such an extended and scaled version of the theory, which is required to analyse and study passages describing mechanisms, and their teaching narratives. The elements in such passages and their pedagogy (sentences, narratives, and technical terms) are tightly interconnected structurally and conceptually, and they together instantiate the mechanism model.

A second challenge is extending distributed cognition (DC) theory, particularly to develop an account of the way internal mechanism models develop through a convergence of external representations and narratives. Current accounts of DC mostly focus on divergence cases, where ERs move cognitive processes outside the head, and thus help lower cognitive load (Hutchins, 1995a, b, 2000). The use of ERs to generate and augment imagination, and thus build internal models, is less examined. Existing work in this space mostly focuses on the building of external artefacts—such as computational simulations and laboratory devices (Aurigemma et al., 2013; Chandrasekharan & Nersessian, 2015, 2021)—and the way these help augment imagination, and result in discoveries and innovations. In the mechanism learning case, a distributed system of ERs (textbooks, teacher narratives, technical terms, diagrams, gestures) is used to build a new mechanism model in learners' minds. This process is similar to a discovery, but for the individual student, rather than for humanity as a whole. The models thus generated can be activated later by the ERs, particularly by mechanism terms (MTs). This is an outside-to-inside distribution of cognition, where representational networks outside lead to a new conceptual network inside (Hutchins, 2000). Existing empirical studies of this process (Martin & Schwartz, 2005; Rahaman et al., 2018) focus on students' use of artefacts to learn new concepts. Convergence of ERs and teaching narratives in a guided way, to form new mechanism models and terms in student minds, is not studied much from a DC perspective.

Extending this theoretical view, and related empirical results to the process of generating mechanism models in student minds, the problem of understanding passages describing biological mechanisms could be seen as a process of running a dynamic mental model, where perceptual neuronal networks encoding sensory experience help activate imagery (such as leaves, stems, stomata; components and their structure), and neuronal networks encoding motor experiences help "dynamicise" this imagery (dynamics of the guard cell). Understanding mechanism passages would thus involve running a mental simulation of the structure and activity states embedded in the passage (Mak & Willems, 2019).

In this account, for a teacher to develop an understanding of the canonical mechanism described in the textbook, she needs to first activate neuronal networks that instantiate sensorimotor models that form the mechanism structure (such as stomata, guard cells), and then the mechanism-specific structural and dynamic configurations they generate (such as turgidity, transpiration). As most of the mechanism components and the dynamics are imperceptible, and quite different from everyday experience and their language forms, it is very unlikely that the teacher would have a ready sensorimotor experience to draw on, to ground these novel structures and processes. Thus, the teacher's comprehension of the mechanism requires reconfiguring or recombining her sensorimotor experiences, particularly ones that are most similar in dynamics to the described mechanism (Rahaman et al., 2018; Schubotz, 2007). She then needs to integrate these reconfigured neural activities to generate the mechanism model. Note that this reconfiguration process is driven by the text. Language here functions as a system that helps activate, recombine, and finetune mental simulations.

To transfer this mechanism model to students' minds, the teacher needs to do another reconfiguration, to adapt her simulation model to students' existing models and experiences, and also their language abilities. For this, she juxtaposes common student experiences (such as blowing into a balloon and seeing it expand) in relation to the mechanism, and then maps this sensorimotor experience systematically to her own model of the mechanism, thus acting out in the classroom the imperceptible structure and dynamics, using a narrative the student can follow. Since mechanisms in science have very specific dynamics, which are different from state changes students are familiar to students from their experience of everyday events, the mechanism state changes are labelled using special technical terms. The teacher invokes these terms in tandem with the teaching narrative, so that they are associated with the narrative of the mechanism.

At the students' end, ESTL suggests that attending to the narrative of the teacher generates a mental simulation process, where the learners' perceptual and motor systems are activated virtually/covertly, to generate an approximate version of the structural components of the narrated mechanism (such as the balloon and guard cells) and their dynamics (opening and closing). These simulations are then associated with the mechanism terms (MTs). Understanding of MTs thus emerges through the process of students simulating the integrated dynamics (of the balloon narrative and the guard cell drawing). The teacher's invoking of MTs with the dynamic model allows "loading" (Redish & Kuo, 2015) the new integrated structure and dynamics into these MTs. In most cases, this loading is a gradual process, based on many intermediary ERs (such as metaphors, drawings, gestures, etc.), which the students "bind" together, to generate the specific simulation that is loaded into the MT.

Once the mental simulation and the formal symbolic terms are thus intertwined, encountering the MTs can reactivate—and also focus attention on—specific parts of the mechanism simulations (such as guard cells, and turgidity), or the mechanism simulation as a whole (such as transpiration). Since such later encounters with MTs activate mental simulations, these terms acquire a "performative" nature, making them similar to action verbs (such as kick, pick, and suck), which have been shown to generate covert motor activation (Bergen & Wheeler, 2010; Bub & Masson, 2012; Glenberg & Kaschak, 2002; Matlock, 2004; Pulvermüller & Fadiga, 2010; Wilson & Gibbs, 2007; Yee et al., 2013).

However, the mechanism terms (MTs) are more complex than verbs, as they have the following features:

- They are built up through extended teacher narratives and enaction.

- They are generated through reconfigurations of sensorimotor experiences, artefact states, and mental simulations.

- They thus have intricate—circuit-like—internal structure, which can change systematically, based on new experiences and narratives that are embedded in the MTs.

- They are "stacked" to form mechanism complexes.

They can be finetuned and used to focus attention on specific parts of the mechanism.

- They activate mental simulations of inanimate movement.

These novel properties, and the detailed simulative nature of MTs, make them different from verbs. Such terms are better thought of as "performative bundles," as (1) they contain intricate internal structures that can activate mental simulations in specific and nuanced ways and (2) they are built up through a series of teaching actions. We term this process— the enactive building of such bundles—performative bundling.

A significant problem in building up such bundles is the "correct" activation of the mechanism simulation in student minds, such as the right orientation, mapping, and sequencing of transformations, as the teacher narrative may not cover all these aspects in full detail. This suggests students initially generate only a "gist" simulation of the mechanism, based on the teacher's enaction. These student simulations will be patchy and at a surface level, providing just a summary understanding based on the teaching narrative.

For instance, in the case of transpiration, the student may not comprehend the opening and closing mechanism of the stomata as given in the text, 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 allows some gases to be exchanged. Later, when the opening and closing of the stomata are invoked in another context, only this summary simulation will be activated. The nature of this simulation would vary significantly between students, depending on their real-world experiences, reading comprehension, and attention.

This gist simulation is an important operational element in the classroom context. The teacher, through her own understanding and experience of teaching a topic, as well as her knowledge of how a topic progresses in subsequent grades, settles on a particular level of gist simulation, which she enacts, using the blackboard, gestures, and narrative. This distributed, but tightly scoped, enaction process, which is a key component of teachers' "armamentarium" of pedagogical content knowledge (Shulman, 1986), helps class participants to converge their own individually varied simulations to a common core, creating a shared understanding. The teacher then builds on this shared structure, to develop more complex aspects of the mechanism. The gist simulation also helps her design structured discussions and evaluation schemes to test student understanding.

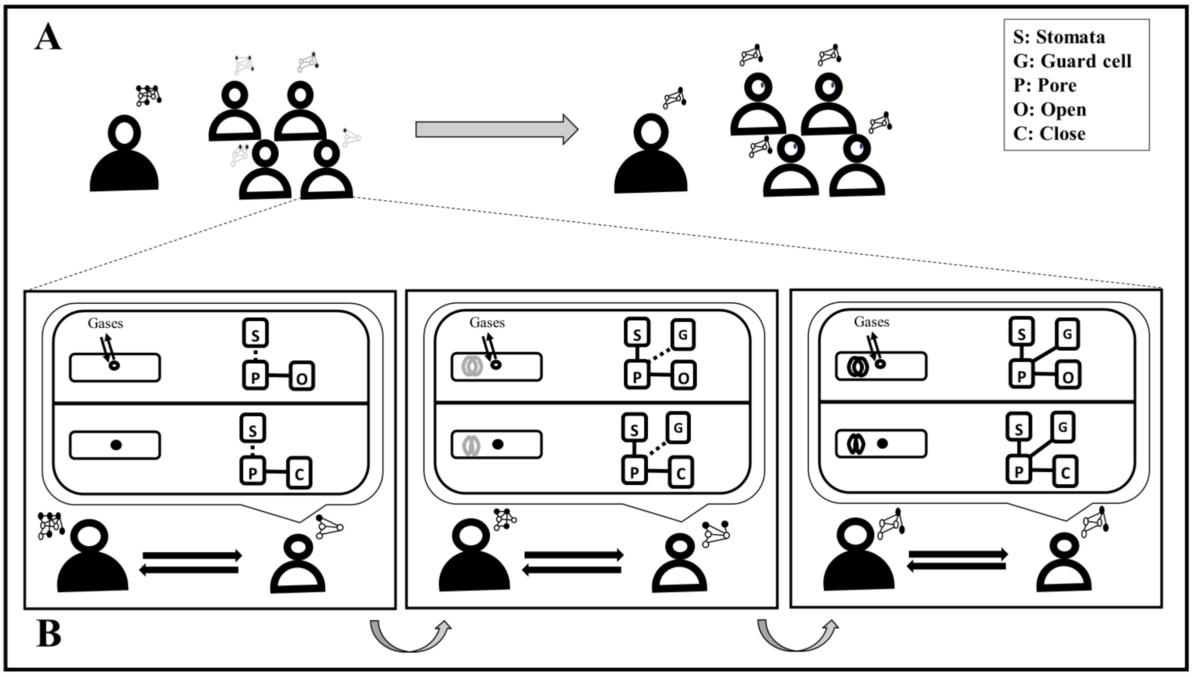

Figure 4.11 The formation of a gist simulation of a mechanism.

Panel A illustrates the convergence of teacher and student simulations, through the teacher's classroom activities and discussions. Initially, the teacher starts with a complex simulation of the mechanism she is trying to generate in students' minds. Based on the feedback from students, she gauges the difference between her simulation and the diverse student simulations. She then adapts her initial simulation, to build a gist simulation, which can help refine most student simulations. Panel B shows an expanded version of this process, for a single teacher-student interaction, using the transpiration example. The teacher builds on the student's minimal simulation of transpiration, by introducing guard cells and later *consolidating this addition, through construction of a performative bundle, as illustrated in Fig 4.2*

Figure 4.11 captures how the ESTL model could be used to understand, in an integrated fashion, this complex classroom dynamics towards convergence, based on the balloon example.

The gist simulation and the related building processes are distributed cognition processes, spread across the teacher, students, and classroom artefacts. In the next section, we examine possible ways to extend DC theory to account for these processes.

4.5 The Distributed Generation of Internal Mechanism Models

Recent work in distributed cognition (DC) has explored the way building processes generate new imagination processes. These studies are based on analyses of frontier researchers' building of, and interactions with, computational models and their visualisations (Aurigemma et al., 2013; Chandrasekharan, 2009; Chandrasekharan & Nersessian, 2015; Chandrasekharan et al., 2012), to advance discoveries and innovations. In this analysis, the process of building the external computational model leads to a "coupling" between this ER and the researchers' imagination. This coupling allows changes made in the ER to smoothly change the imagination, and vice versa. From a neural perspective, the coupling of the ER to the imagination can be understood as a form of "incorporation" (Maravita & Iriki, 2004), similar to the way tools become part of the neural body schema through their use. Maravita and Iriki (2004) review many studies that show such extension of the body schema, where the use of tools leads to what they term "incorporation," where the tool extends the tool-user's peri personal space (the "action-oriented" space around the hand, which is coded by specific neurons). After tool use, the neurons coding for peri personal space respond to stimuli at the tip of the tool, indicating the incorporation of the tool into the body schema. This incorporation process extends the action space of users—to include actions using the tool—and also their mental simulations about possible actions in a given context (Maravita & Iriki, 2004; Làdavas, 2002). Recent DC analyses argue that new scientific discoveries and innovations emerge from such incorporation processes, where actions with models and instruments radically change the nature of imagination, making it more coupled with physical actions, and thus enactive (Chandrasekharan, 2014; Chandrasekharan & Nersessian, 2015, 2021). This incorporation analysis has recently been extended to develop an enactive cognition account of young students learning computational thinking in kindergarten, using robotic toys (Sinha et al., 2023).

The building of new mechanism models in classrooms can be understood as roughly similar to this coupling and incorporation process, as the teacher's enaction and related structures (narratives, diagrams, gestures)—which are external—activate learners' imagination (covert activation of sensorimotor networks), and change this process to generate new mechanism models.

However, unlike the case of frontier researchers building computational models for discovery, this coupling is not a continuing one, but occurs only sporadically in the classroom. Also, the enaction and imagination are performed by different sets of agents (teachers/students). These processes also change based on student/teacher questions and other classroom dynamics. The coupling here is thus a constantly changing "web" that is spread across brains.

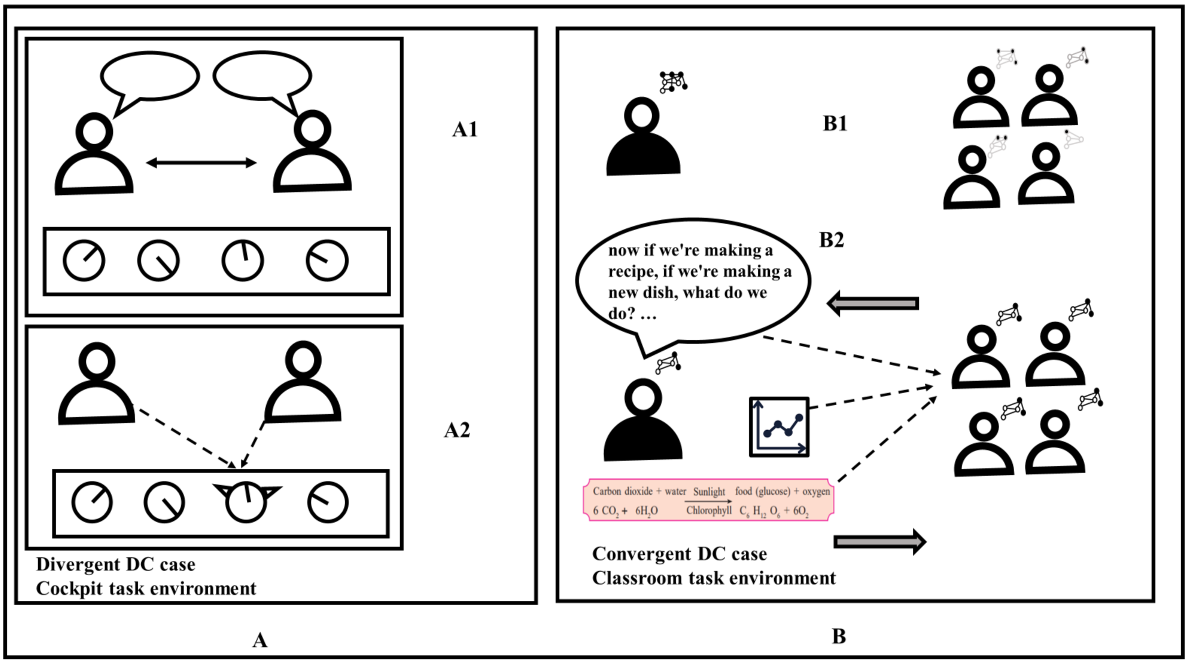

Figure 4.12 A comparison between the inside-to-outside divergent (A) and the outside-to-inside convergent (B) model of distributed cognition (DC).
Part A (adapted from Chandrasekharan & Tovey, 2012) illustrates the divergent DC model. Panel A1 shows the task before the speed bug representation was designed for cockpits. Here, the pilots have to do computations in their heads and coordinate with each other. Panel A2 illustrates the task after the speed bug representation (triangles on the dial) was designed. The speed bug allows both pilots to coordinate their actions by perceiving the instrument panel states in relation to the settings of the bug. The speed bug thus allows "offloading" of cognitive processes to the external world. Part B1 illustrates the convergent DC model. B1

shows the teacher and students, with different initial internal mechanism models, based on their accumulated enactive experiences. As the teacher starts explaining (B2), the external structures she uses—such as the teaching narrative (which may include analogical and metaphorical mapping) and gestures—intertwine with other ERs, to generate a coherent mechanism model in students' minds. The solid arrows at the bottom indicate that this convergent process is iterative, as the teacher revises the explanatory episode, based on student responses

This coupling process leads to a performative bundle in each individual brain. The bundle can later invoke the teacher's enaction and related ERs, in a decoupled way, i.e., without requiring the generative ERs and narratives used by the teacher to be present. For instance, when the MT is encountered during evaluations (quizzes, exams, lab work), the learner needs to reactivate the mechanism dynamics in a stand-alone fashion, without the support of the external structures the teacher used to build the mechanism in the classroom. This process is unlike the computational modelling case, where the imagination is closely attached to the ER and its manipulation.

The coupling and incorporation in the classroom lead to a tight intertwining between different mental simulation networks (related to the balloon, drawing, narrative, gestures) and an MT. As the MT points to—and can thus activate—this bundled simulation network in very specific ways, the MT can be thought of as functioning like an active digital tag, which can activate complex computational processes even when encountered briefly. This view of MTs allows some of the standard DC analysis related to external artefacts to be extended to internal cognitive structures. For instance, as an active mechanism tag, MTs can work as a coordination system for imagination in a classroom, as MTs can be used by teachers and students to co-activate similar dynamics across different cognitive systems. The tags also make possible new operations, such as novel reconfigurations that bring together MTs, based on new phrase structures in teacher narratives. The new language structures can focus on the activation of mental simulation networks, extend these, combine them with other simulation elements, etc. In particular, this manipulation feature can be used to build up the mechanism model further, by interlocking new mechanism elements with the tag—such as light-dependent reactions and the Calvin cycle in the photosynthesis case—to build mechanism superstructures. The tag model also supports different levels of activation of the mental simulation network, such as just the recognition of the tag (surface level), the tag acting as a pointer and activating all associated mental simulations (deeper level), the clustering of different tag activations to form new named categories of dynamics (wider level), etc.

A related DC process could be the way the tags support the finetuning and extending of executive control, similar to the way tool use and language use shape such control (Vygotsky, 1978; also see Hutchins, 2000). In Vygotsky's model, tool use by learners, in combination with language use, is considered to develop a two-pronged control, where the learner develops the ability to control both her environment and her reaction to it—i.e., both the world and oneself. As MTs have both tool and language properties, the development of learners' imagination through mechanism models and MTs could contribute further to these control effects. The learning of mechanisms could thus be understood as a special instance of the Vygotskyan model, where humans combine tool use and language use to develop novel control capabilities. This analysis—where building of internal mechanism models and terms is seen as similar to building of artefacts, with the "loaded" MTs extending imagination, coordination, and control, in ways similar to artefacts—provides a new DC approach to understand science learning.

The above analysis focuses on what teachers do in classrooms to promote the learning of mechanisms. In the next section, we extend this analysis to the nature of academic language (AL), and how the structure of this external representation promotes the learning of mechanisms. This account of AL—using the specific case of nominalization—also illustrates the broader analysis possibilities offered by the performative bundle approach, as it helps characterise the wider problem of learning academic language.

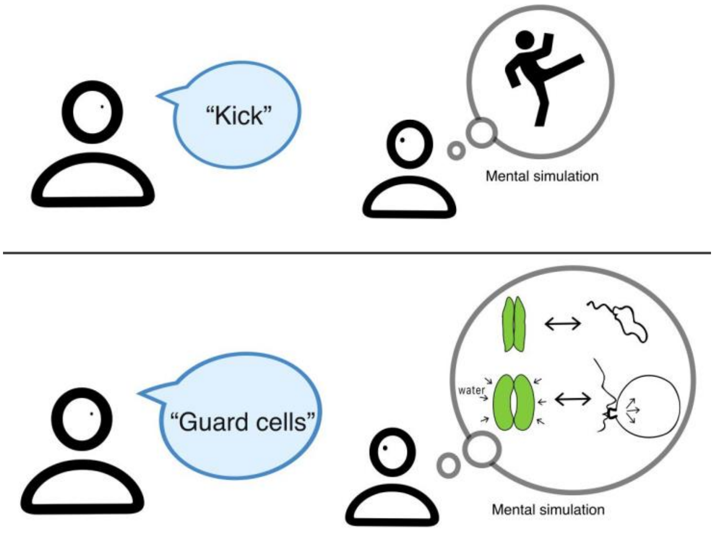

Figure 4.13: The ESTL basis of the Performative Bundle construct
According to the ESTL, the word "kick" would activate a mental simulation activating the memory traces of sensory motor experiences related to kicking. Similarly, the PB construct proposes that a teacher fills the Mechanism Terms with dynamicity, by mapping students'

sensorimotor experiences with abstract mechanism terms in very specific ways. This mapping is done with the help of several enactive strategies, such as the use of analogies, different external representations (such as figures, equations), gestures etc. It is expected that later on, whenever the student encounters these PBs, it would activate a memory trace of these experiences bound together in the bundle, and trigger a gist mental simulation of the mechanism.

4.5.1 What is not a performative bundle?

The theoretical construct of the performative bundle emerges from the extension of ESTL to teacher narratives used in the explanation of mechanism models in the classroom. It conceptualises mechanism understanding as driven by mental simulation. Thus, in the teaching/ learning context, anything that is not likely to activate a mental simulation would ***not be a PB***. An example would be biological classification; here the taxonomy of organisms is presented (in the textbooks and the teacher narratives) in a way that requires memorisation, without much comprehension. Similarly in non-biology contexts (such as physics) the learning of derivations in an algorithmic way relying just on mathematical manipulations in a rather mechanical way, without making any connection to reality, would be another example of AL use that would not be a PB.

Given the examples above, a note of caution becomes imperative. We have argued that whether a piece of language is a PB or not depends on the activation of mental simulations, based on sensorimotor experiences. The range of what would be a PB for someone could for example increase through learning a language or by simply living in the world and gaining sensory motor experiences. The steps in a derivation when learnt in an algorithmic way would not be a PB, but if the same steps are taught/learnt by systematically connecting them to real world and sensory motor experiences – by "loading reality" into them – the learned derivation would qualify as a PB.

Chapter 5: Physics Derivations and Enactive Equations - Extending the Performative Bundling Account

In this Chapter:

The process of building mathematical models in physics (derivations) is typically taught as a step-by-step algorithmic process, especially in developing countries. Interactive technologies provide novel ways to restructure this dominant teaching narrative, in ways that allow students to learn physics model-building as a conceptual, and thus more general, process. We outline such an interactive system, which builds on – and extends – the performative bundle account. The performative bindle account on its own does not account for the disciplinary idiosyncrasies of physics such as the semiotic resources used. We make use of a recent account of physics model-building as the process of 'loading' reality into mathematical equations, and the cognitive science framework of concreteness fading, where a less idealized representation of reality is gradually morphed into a more idealized representation. To test the effectiveness of this system – in teaching physics model-building in a non-algorithmic way – a teacher-researcher used the system to teach 10 students, in one-to-one mode. We then tested students' understanding of the general 5-step sequence involved in physics model-building, the related enactive understanding of equations, and students' ability to extend the 'loading' view of model-building to a moderately open-ended problem. Results showed that the system allowed students to internalize the 5-step sequence. However, students were only partially successful in extending this sequence to the open-ended problem.

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[3] *This work was done in collaboration with Ambar Narwal (PhD candidate Cognitive Science Program, Indiana University, Bloomington, USA,). Excerpts from a manuscript that we have been working on, have been used in this chapter.*

5.1 Introduction

Language takes a context specific form called the register. Each discipline presents a different context in terms of the objects of study, the nature of knowledge (Hofer, 2000; Neumann, 2009), the different representational resources employed (Brizuela & Gravel, 2013) etc. In Physics for example reality is modelled and represented in terms of mathematical equations. This transition from concrete to abstract occurs gradually in steps, over an extended period of time (for more details, refer to section??). In biology too we encounter a similar transition from the concrete to abstract, but it is less frequently compared to physics. Biological systems present a challenge to mathematical modelling due to their immense complexity. Discovering mechanisms of action in cellular processes has been a major paradigm in biological modelling.

Many major discoveries in biology have been mechanism models. These differences in fundamental disciplinary aspects also get reflected in the language of the discipline. This forms a major source of difference among academic registers. Each discipline has evolved a specialised form of language to deal with the nature of knowledge specific to it.

Disciplinary differences related to student difficulties – in terms of the language used, the different representational resources employed etc. – are well documented (Hofer, 2000). To explore whether the PB account could be extended to other disciplines, particularly to design new teacher narratives, we examine the applicability of the performative bundle account to the case of physics derivations. In the biology cases as discussed in Chapter 4, we showed how biological mechanisms, and their conceptual structures, can be considered as active and performative entities, and how this changes our view of pedagogy. Compared to biology, physics contexts involve increased levels of abstraction. This conceptual structure is reflected in AL – through the widespread use of mathematical equations and other formal systems. These abstract systems are usually treated as symbolic/representational entities, in both the cognition and learning sciences literature. In this chapter, we present an account extending the PB account (Salve et.al., 2024), where we show how equations can be considered as enactive entities, into which aspects of reality, particularly change, is systematically loaded. This approach is similar in spirit to treating technical terms (like guard cells) as performative, and the way these performative entities are stacked to generate more complex mechanisms (like photosynthesis). In this view, the parsing of a typical physics context thus requires mentally simulating the technical terms, which are PBs (similar to the discussion in biology) as well as mathematical equations, which also function as PBs. Extending this view, the role of the teacher is to generate narratives that facilitate mental simulations for both the mechanism/technical terms and the mathematical equations.

A second theoretical advance presented in this chapter is the extension of the PB account to the building of a conceptual structure itself, rather than just its pedagogy and learning. The biology account we outlined in the previous chapter only showed how the teacher builds established mechanism models in student minds, using performative elements such as metaphors. We did not provide an account of the way an established mechanism is itself built by the discipline. This process is nebulous in biology, but it is more explicit and streamlined in physics. This systematic building structure allows students to be taught the process of building a physics mechanism model (i.e. an equation). Learning the process of building canonical physics models (usually termed a derivation) is expected to allow students to build their own equation models, particularly to solve open-ended problems. We present an enactive account of the process by which a derivation builds an equation. This account considers equations as PBs, and the process of building equations as the process of loading reality into an enactive symbolic structure.

Building the enactive account of equations involved developing a new educational technology – in the form of an interactive system that embedded the loading narrative above. We study the effect of the interactive system along with the associated narrative of an experienced physics teacher while the students interacted with the system. An important difference in this case is that the previous analysis is based on a minimal classroom, where the teacher's access to technological applications is limited. Here we examine how teacher narratives could be changed, and also augmented, in combination with an interactive system. Note that this system was designed specifically to generate a new teacher narrative, and thus a new kind of student understanding of physics derivations.

We outline the design and testing of this interactive teaching system. The design sought to help teachers develop a new model-building narrative of derivations, and thus help undergraduate physics students develop a model-building understanding of derivations, particularly considering derivations as the process of loading reality into equations (Mashood et al. 2022). The system also sought to develop a new teaching narrative, which allowed teachers to 'enact' (rather than describe) the building of a canonical model in physics, and thus advance undergraduate physics students' model-building capabilities. This interactive system would allow us to explore whether, and how, students internalised this new building narrative.

5.1.1 Derivations: Loading reality into equations

Derivations included in textbooks are the final products of extensive model-building by scientists (Nersessian, 1992; Knuuttila & Boon, 2011; Bokulich, 2015). This building process significantly involves analogical thinking and building of spatial models, and complex reasoning based on both these elements (model-based reasoning, Nersessian, 1992; 2010). Model-building also requires conceptual blending, a complex cognitive process where existing concepts are brought together in new ways, to generate new concepts (Fauconnier & Turner, 1998; Hestenes, 2006; Hrepic, Zollman, & Rebello, 2010; Kuo et al., 2013; Van Den Eynde et. al., 2020). A famous instance is the way Maxwell arrived at his equations of electromagnetism by blending continuum mechanics ideas, the initial models and results developed by Faraday, and a 'vortices and idle wheels' visualisation (Nersessian, 1992). This blending process involved many complex imagination and reasoning steps, based on analogy, visualisation, model-building, and model-based reasoning (Nersessian, 1992; Bokulich, 2015).

Interestingly, Maxwell only captured these blending, imagination, and reasoning processes systematically in his notebooks. He did not include these steps in his final mathematical model. This kind of 'wiping' of the extended model-building processes involved in the development of the equation – the key cognitive process in physics – is a common theme (see Mashood et al. 2022, for a discussion). As a result, textbooks include only a linearized, sanitised version of the mathematical model presented by Maxwell, and the derivation of Maxwell's equations are thus presented as a series of mathematical steps, starting from other basic equations. Following from this textbook presentation, Maxwell's model-building and reasoning processes are not discussed in most physics classrooms, and the derivation of Maxwell's equations are taught as a sequence of mathematical procedures, in an algorithmic way.

This textbook structure and the resultant teaching narrative has led to a curricular focus on the final formal model, which presents model-building as starting and ending with mathematics. As the derivations taught in classrooms only use the final mathematical rendition of the model, with no discussion of the model-building processes prior to this formal structure, learners are not able to grasp the way the original scientists developed the complex *argument structure* of the model. Learners thus do not understand, or appreciate, the core practice of model-building. The exclusive focus on final models leads to learners understanding derivations as a sequence of mathematical procedures, whose relationships to actual phenomena in the world are not clear.

This lack of understanding of the model building aspects of derivations significantly limits learners' ability to extend the process of modelling (which they learn as the algorithmic derivation of canonical models) to open-ended problems. We propose that this difficulty arises because open-ended problems require many conceptual blending, model-building, and model-based reasoning steps, which are central to the *gradual* building of systematic relationships between real-world structures and mathematical structures. Extending conceptual blending theory, Redish & Kuo (2015) consider this process as the world being 'loaded' into mathematics. In this view, the usage and meaning-making of mathematics in physics classrooms differs from these processes in mathematics classrooms. The key difference is that physics involves 'loading' of physical meaning onto both symbols and numbers. To understand this process in depth, the authors analyse the use of mathematics in physics from the perspective of cognitive linguistics. The case of meaning making in mathematics is considered as a subset of a broader cognitive process – the way human beings make meaning out of language. This analysis draws on the roles played by embodied cognition and context sensitivity in the dynamic process of meaning making.

The authors substantiate the proposed notion of loading using a `modelling cycle', which describes the interconnections between the physical system and the associated mathematical representation. This cycle is mediated by four steps – modelling, processing, interpreting, and evaluating. The first step - modelling - is conceptualised as involving the `mapping of identified measurable aspects of a physical system into mathematical symbols. The mechanism underlying this mapping is then elaborated in terms of Sherin's idea of symbolic forms and conceptual blending (Sherin, 2001).

The 'loading' approach to meaning-making provides valuable insights into the nature of model-building. However, this analysis is structural, in the sense that the authors do not provide a process account – of how the modeller transitions from the real world into the world of physics, building a model that eventually culminates in an algebraic expression. The account does not outline how/why the final equation can help make predictions, particularly by 'enacting' the behaviour of the physical system the modeller started with. The authors' approach also does not highlight the significance of key modelling moves such as idealisation.

Apart from the process of blending different concepts, solving open-ended problems requires generating new idealised structures (such as new kinds of rigid bodies and other idealised patterns) in the imagination, and formalising these imagined structures iteratively, to generate mathematical models. To learn this process, students need to understand the ways in which imagination and reasoning (involved in analogy and model-building) could be used to generate formal models, and also how these cognitive steps could then be subsumed under mathematical reasoning. This requires a teaching narrative that is very different from the current pedagogical approach to derivations, which is driven by the final formal structures provided by the textbook.

A possible approach to develop such a narrative is concreteness fading, which is a theory of instruction that promotes the systematic sequencing of concrete and abstract materials, to help learners internalise the process of progressive formalisation. It suggests meaningful grounding of symbols, by starting with concrete materials and achieving generalizability by gradually fading to abstract materials. In contrast, the current formalisms-first approach (Nathan, 2012) gives precedence to the use of abstract learning materials (e.g. symbols) in science education, and prevents learners from developing useful intuitions about what these symbols mean (Sherin, 2001). Educational psychologists have argued for the importance of concrete materials in learning, such as story problems in algebra (Koedinger et. al., 2008) and Dienes Blocks in arithmetic learning (Fuson & Briars, 1990). Due to their familiarity, concrete materials activate knowledge elements which aid comprehension in introductory learning contexts.

Concreteness fading mirrors the general sequence embedded in derivations, which requires learners to start with a concrete phenomenon (e.g. motion of a string on a guitar) and gradually model it mathematically (e.g. equation of a wave in one dimension) using abstract materials. In this theoretical framework, derivations can be thought of as gradually morphing a less idealised representation of reality into a more idealised representation (Fyfe & Nathan, 2019, pg. 10). Informed by this approach, as well as the 'loading' model of meaning-making and recent ideas from embodied cognition theory, we designed a set of transitions between different steps in a derivation, and implemented these steps as an interactive learning system. This sequence structured the cognitive experience of the system as an 'enactive process', which allowed the teacher to: 1) help the student co-enact the way one model structure gradually morphed into the next in the derivation sequence, and 2) helped students understand the enactive nature of the final equation, which supports the use of the equations to make predictions.

Here we outline the design and field testing of this interactive teaching system, which sought to help teachers develop a new model-building narrative, and thus help undergraduate physics students develop new ways to think about model-building – particularly as a process of loading reality into equations, based on concreteness-fading. Importantly, the theoretical frameworks we outline above (conceptual blending, concreteness fading) only provided some initial structure to think about the nature of model-building and final equations. They inspired our design, but did not work as full-fledged design frameworks. The next section presents the design of our interactive system for teaching model-building in physics (section 5.2). This system sought to develop a new teaching narrative that allowed teachers to 'enact' (rather than describe) the building of a canonical model in physics, and thus advance undergraduate physics students' model-building capabilities. Section 5.3 outlines the design of an exploratory study that examined the effects of this design, and discusses the results. In sections 5.4 to 5.6 we discuss the collection of data along with its analysis. Here, we also present the results that emerge from this analysis. We close with a discussion of some possible pedagogical extensions of this approach (Section 5.7).

5.2 The design rationale of the system

The interactive system we developed, and the teaching narrative based on it, sought to clearly illustrate the key model-building steps involved in the derivation of the one-dimensional wave equation. This particular way of deriving the wave equation is not part of local textbooks, and it was thus new to students. The novel teaching narrative we developed involved presenting the equation as a *prediction machine*. This approach was inspired by a range of philosophical analyses of model-building in science, including Andrew Pickering's account of the machinic grip (Pickering 1993), recent discussions that consider computational models as 'representational machines' (Chandrasekharan & Nersessian, 2021), and discussions where the laws of physics are considered to emerge from 'nomological machines' (Cartwright, 1997). The prediction machine view, as instantiated by the interactive system, illustrated the way the derivation process gradually loads reality into symbols, to build an 'enactive' equation (i.e. a mathematical structure that 'acts out' the dynamics embedded in it). Further, as the students could follow the model-building process in an enactive fashion (through interactions with the system), the system also acted as a 'manifest' version of the extended process of building a mathematical model. Apart from using a derivation that was unfamiliar to the students, this new teaching narrative was developed using the following novel components:

1) A 'performative' framing of derivation

2) A meta-model of the steps in a derivation

3) Enactive elements at each step.

We briefly describe each of these elements below.

5.2.1 A performative framing of derivation

The overall design of the system was guided by the following framing of derivations, and the interactive system sought to instantiate this framing.

A derivation develops an equation, which works as a symbol-based prediction machine of a real-world phenomenon, based on an idealised form of the real-world system. This machine can perform (i.e. act out) a given real world system's dynamic behaviour (state changes), using changes in numbers in a coordinate system as a proxy. Derivation is the process of building this prediction machine, where at each step the derived structure captures, and 'keeps alive'(i.e acts out), key change events in the real world system. The final equation is thus a machine that is 'loaded' with the dynamic behaviour of the real-world system. As the equation machine is built up from an idealised system, and it is based on variables that capture changes in a coordinate system that works as a proxy for the real world, the equation can be extended to build models of other similar dynamic behaviours in the real-world. Such models act as analogies, which act out, and thus predict (through this enactive performance), the behaviour of systems that are different from the one which was used to develop the equation.

To make the novelty of this performative and dynamic framing clearer, we contrast it below with a purely structural (or 'algorithmic') framing, which we consider to be instantiated by the current textbook-driven way of teaching derivations. This algorithmic approach to teaching derivations is illustrated through a textbook derivation of a wave equation in Figure 5.1.

A derivation seeks to develop an algebraic pattern that matches a given real-world system. Derivation is the process of generating formal and structural steps that systematically turn the real-world system into this algebraic pattern. The final equation is a formal pattern that allows *structuring new real-world situations in ways similar to this algebraic pattern, which allows solving new problems.*

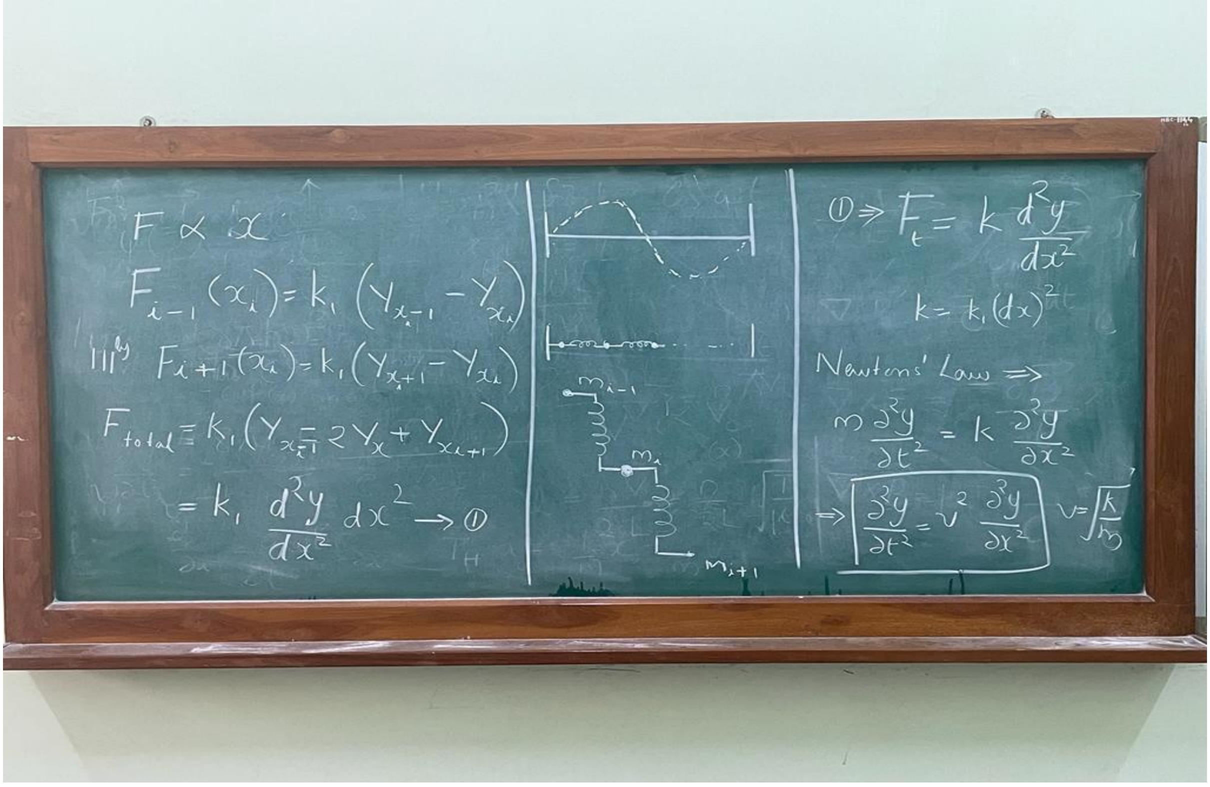
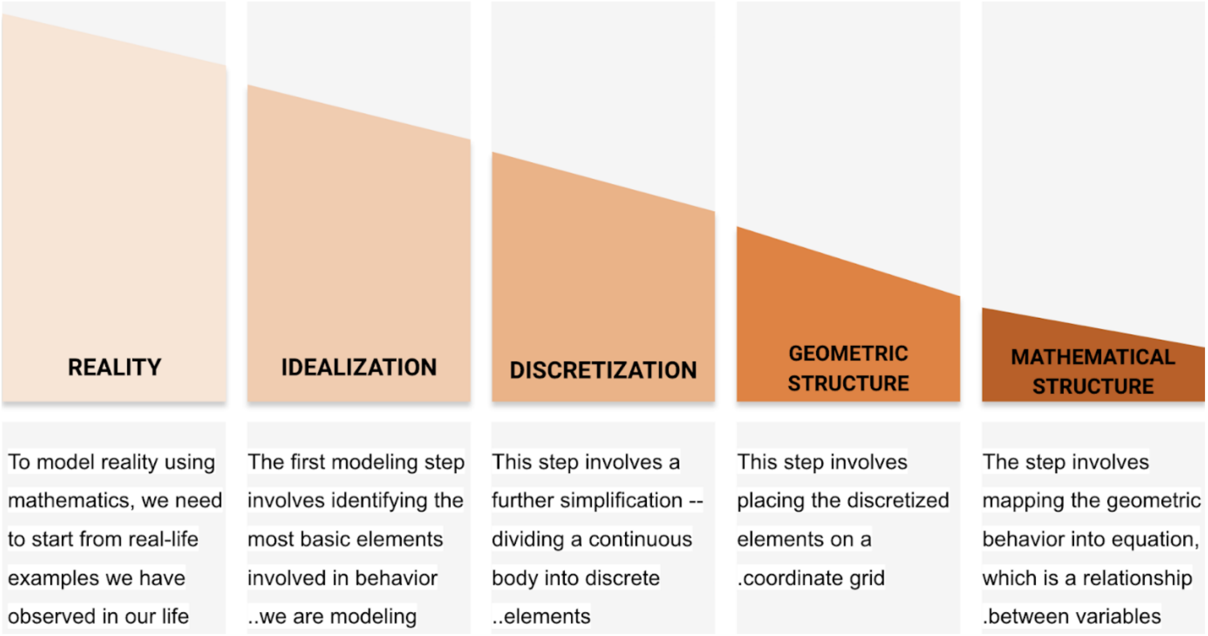


Figure 5.1: Final outcome of the derivation, as taught using the algorithmic method

To operationalise the former performative framing – which we consider to be closer to the actual mathematical model-building process of experts than the latter pattern framing – we developed a meta-model of the steps in the derivation process. This structure is outlined in the next section.

5.2.2 A meta model of the steps in a derivation

We analysed the steps in different derivations in textbooks, and extracted a general 5-step sequence that seems to be embedded in most derivations. This sequence is captured in Figure 2.



To model reality using mathematics, we need to start from real-life examples we have observed in our life

The first modeling step involves identifying the most basic elements involved in behavior ..we are modeling

This step involves a further simplification -- dividing a continuous body into discrete ..elements

This step involves placing the discretized elements on a .coordinate grid

The step involves mapping the geometric behavior into equation, which is a relationship .between variables

Figure 5.2: The converging sequence of 5 steps followed in most derivations

This analysis was motivated by discussions on scientists' modelling and reasoning practices – particularly the practices of Maxwell and Carnot – developed in the philosophy of science literature (Nersessian, 1992; Knuuttila and Boon, 2011), and extensions of them by physics education researchers interested in modelling (Hestenes, 2006). The philosophy of science analyses show that the derivations outlined in textbooks are condensed and linearized final versions of extensive model-building and model-based reasoning by scientists. This view suggested that there would be pedagogical benefit in highlighting the reasoning processes underlying textbook derivations. We therefore analysed derivations through a model building lens, to capture some of the crucial modelling moves that were `wiped' (Mashood et al., 2022) from the final versions that are presented in textbooks. Our analyses included many textbook derivations (including moving pendulum, oscillating string, Bernoulli's equation, gyroscope, efficiency of heat engine, wave equation, and many others). These were drawn from popular books used at the introductory and early undergraduate level (Halliday et al., 2001; Young and Friedman, 2004; Kleppner and Kolenkow, 2014; French, 2003; NCERT, 2006). The broad goal was to understand and isolate the *general* cognitive processes involved in derivations. This analysis was not based on any explicit rubric, but was guided by readings and discussions as part of a graduate course offered by the second and last authors, and also related explorations with physics researchers and teachers. The analysis primarily involved identifying *recurring* modelling moves, particularly ones that were of pedagogical value. For example, our readings and related discussion indicated that *idealisation* (second step in the 5 steps in Figure 2) is a key recurring move in all model-building. This move enables the transition from the rich and experiential real world to the structural and dynamic world of physics, and it is thus a *generic* conceptual structure underlying all derivations. Another required transition we identified was the embedding of the idealisation in a coordinate system (*geometric structure* step in Figure 2), which enables quantification, and thus eventually the building of the equation. The geometric characterization of the idealised system (point masses, rigid bodies etc.) is required for this transition to the coordinate system, as amorphous structures are difficult to embed in a coordinate space. Similarly, we reasoned that the equation that is developed through the model-building process (*mathematical structure* step in figure 2) provides only a *description* of the idealised system, which does not capture the *generic* mathematical relationship between the system variables. This systematic relationship is arrived at through the process of *solving* the equation, which isolates a family of curves that captures the *generic* behaviour of the system that is modelled. This step is not included in our 5-step sequence, partly because solving (particularly analytical approaches to solving) is overemphasised in textbooks and teaching, and partly because our analysis and system design was part of a larger project that sought to introduce numerical approaches to solving equations, allowing physics students to transition systematically to computational modelling (Mashood et al., 2022).

The 5 model-building steps we arrived at through the above analysis are outlined using simple examples in Figure 5.3. Both these examples begin with real world scenarios of oscillatory motion and end with mathematical equations. It is important to note that the movement from idealisation to geometric structure can involve many intermediate steps, depending on the complexity of the real-world case. The two examples shown in Figure 5.3 are simple, and do not involve the discretization step, because they explain point mass systems. Our interactive system uses the 5-step sequence as shown in Figure 5.2.

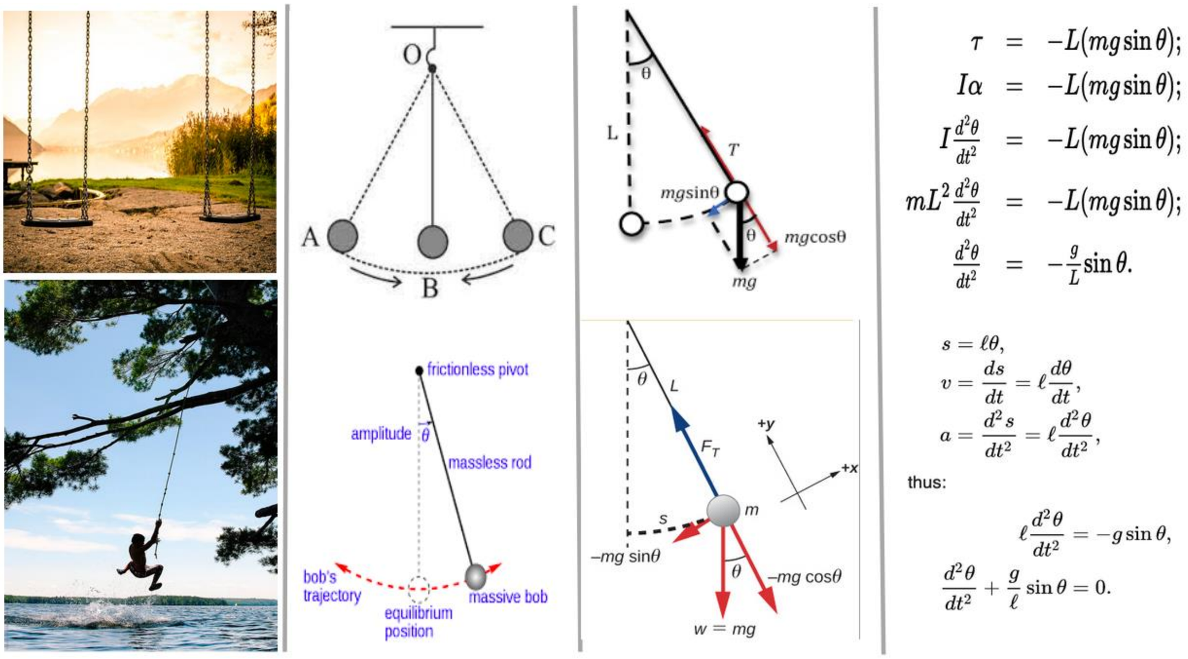


Figure 5.3: Conceptual steps followed in most derivations, illustrated using two simple examples.

We use the example of modelling the motion of a string fixed at both ends.

Reality: We first start with real life examples or situations and then gradually transition towards a mathematical equation that would enact its behaviour which we started out to model with. In our case the guitar or a suspension bridge could be appropriate examples.

Idealisation: It is the first modelling move. Here the system is decoupled from the real world and a representation or schematic in terms of mathematical entities is constructed. The relevant elements in the behaviour of the system we are trying to model are identified and focused on. The features of the system such as colour, shape etc. which are not relevant to our question of interest are not considered. It is important to note here that the features of the system that are considered for the modelling depend on the behaviour of the system being modelled. In our case we consider the dynamic behaviour of the vibrating string. In order to develop a simple mathematical model of the dynamic behaviour of the motion of the guitar string we start by considering these systems as one-dimensional strings tied at both ends.

Discretization: This move involves further modelling the idealized one-dimensional string as mass points connected together by small springs. Essentially this step involves dividing a continuous body into discrete elements which in turn will make the application of Newton's laws easier. Since the functional form of spring forces are known we can easily find the total forces acting on any arbitrary mass point so that the analysis can eventually be conjoined with Newton's second law.

Geometric structure: The transition from a discretized system to a mathematical equation involves a further crucial modelling move. The discretized system is placed in a coordinate system or mathematical grid and explicit mathematization ensues. The different forces are represented by vectors which are then resolved into components. Also, the relevant variables and parameters are chosen and explicitly stated.

Algebraic equation: Usually the last step in a derivation, this step involves mapping the geometric stage into algebra, an equation which is a relationship between variables. In our derivation, we summed the total force acting on a mass point, generalized it, and represented it as a differential equation. The solution to this equation captures the behaviour of the motion of a string fixed at two ends. This step marks the completion of the gradual and systematic loading of the real-world to a mathematical equation.

The converging sequence in Figure 5.2 allows visualising the derivation as a process that slowly transforms the real-world system, so that it can be 'loaded' into mathematical symbols. In the interactive system, this 5-step sequence was also used as a clickable interactive element, which allowed navigation between the 5 transitions in the building process. Learners could move through the derivation steps, broadly based on this 5-step sequence. Each step was outlined and illustrated using a figure, until the algebraic version. To reinforce the 5-step sequence, it was also provided separately as a progress bar at the top (Figure 5.4). This converging structure of derivations was also emphasised in the beginning and the end of the interactive system (Figure 5.5).

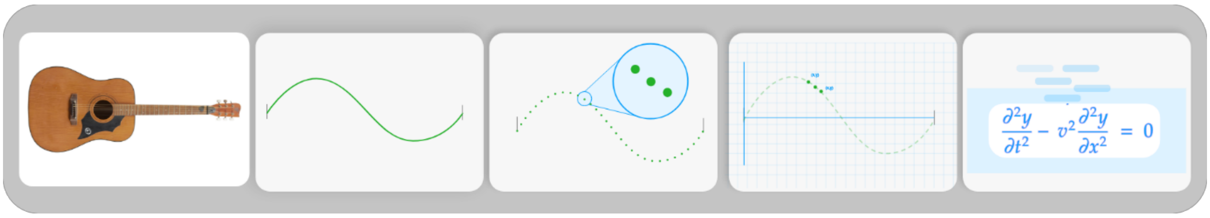


Figure 5.4 Progress bar sequence placed at the top section of the interactive system. *Clicking either of these steps navigates learners to that stage in the derivation sequence.*

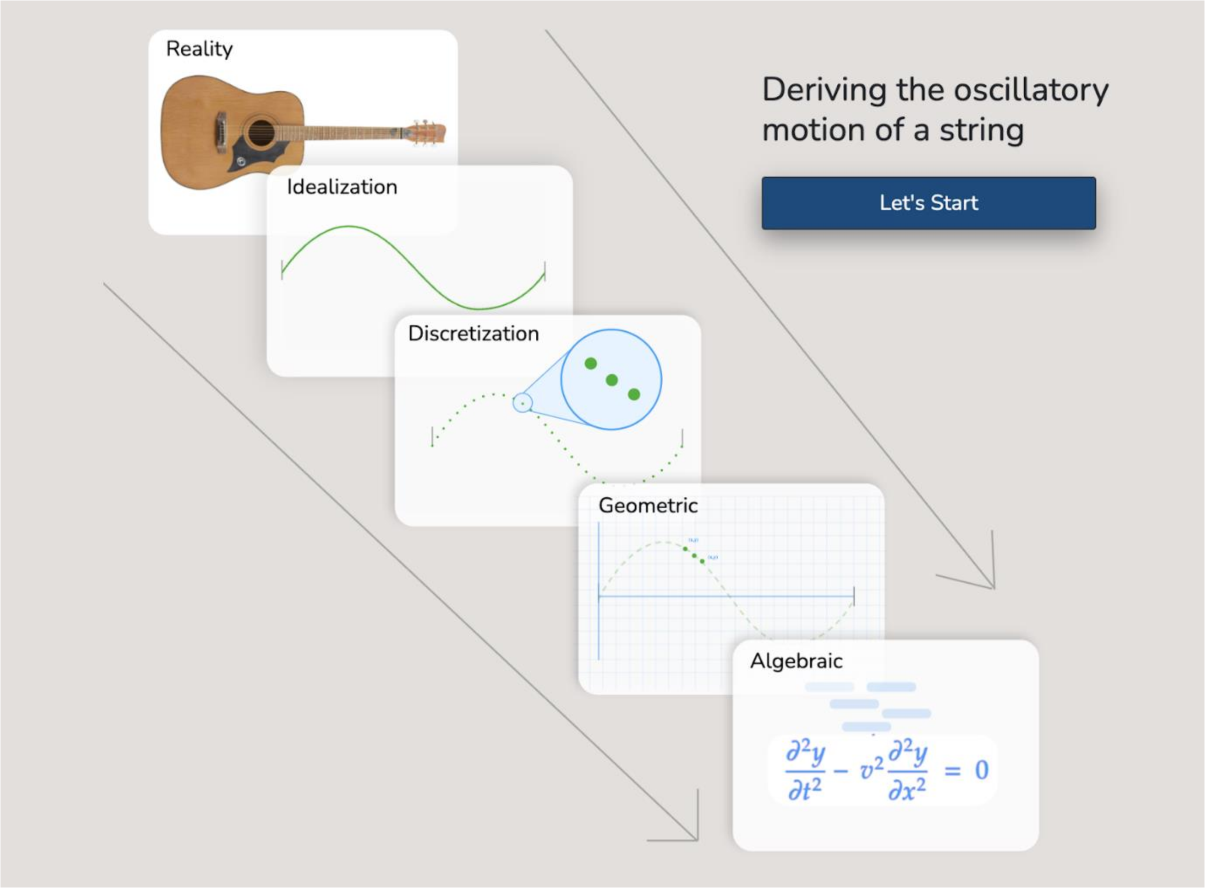


Figure 5.5 A 5-step sequence emphasised at the beginning and end of the interactive system.

5.2.3 Enactive elements at each step

To make the performative character of the equation and the derivation process better available to teachers and learners, enactable visualisation elements were added to the interactive system. First, the process of equations ‘acting out’ the behaviour of phenomena in the real world (Majumdar et al., 2014) was illustrated using a novel simulation system, which showed the equation’s variables changing in tandem with changes to the real-world system and a graph. Before interacting with the derivation system, learners were asked to manipulate different states of this simple pendulum simulation, to develop a qualitative sense of the equation-as-machine notion.

Secondly, in the derivation system, learners were provided ways to manipulate the on-screen activity at most points in the 5-step sequence. This allowed the real-world activity that eventually became the equation to be ‘kept alive’ at each of the transformation stages. The active manipulation was also designed to engage the students’ sensorimotor system, so that later recall of the equation would include this sensorimotor activation (mental simulation). Finally, the manipulations, which augmented the continuing thread of real-world activity embedded in each step, were designed to promote integration of the different derivation elements, by extending the action system's inherent capability to integrate many sensorimotor elements. Since the process of derivation involved starting from a concrete representation and progressing towards an abstract one, the design of these enactive elements also incorporated recommendations driven by the theory of concreteness fading (Fyfe & Nathan, 2019). Figure 5.6 describes how learners interacted with enactive elements at each step in the derivation system. Some interactions involve dragging of sliders while in others, learners interact directly with iconic elements.

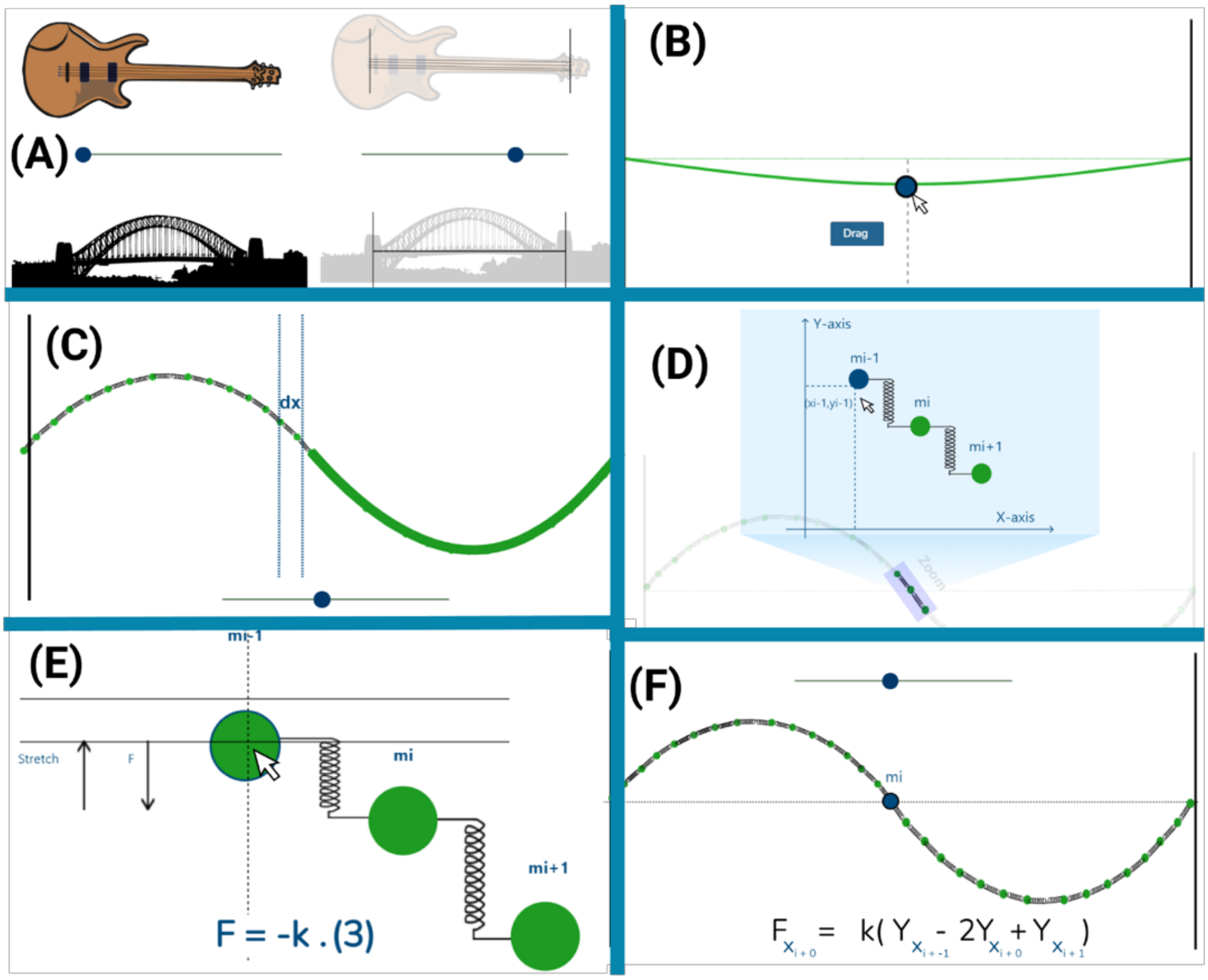


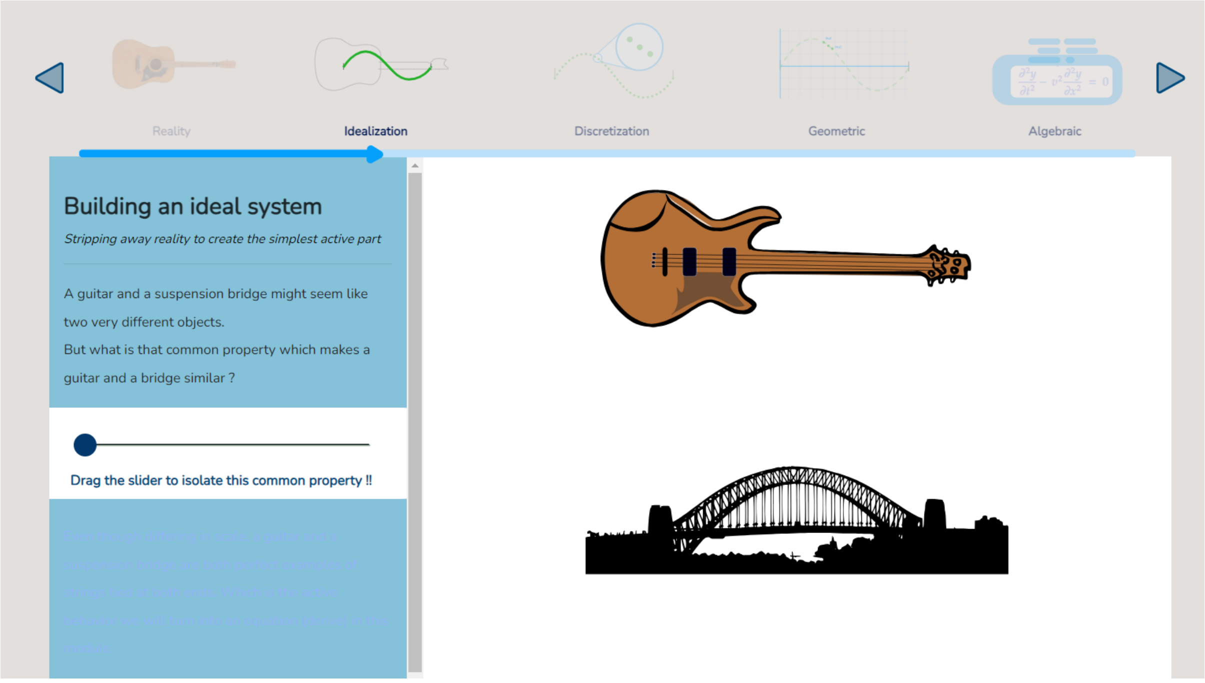
Figure 5.6 Enactive elements used in the derivation system.

(a) Dragging the slider idealises the concrete representations of a guitar and a suspension bridge into a one-dimensional string. (b) The idealised string's behaviour can be explored by dragging it upwards and downwards at different points. (c) The idealised string is discretized into small mass points by dragging the slider. (d) Scrolling over the three highlighted mass points on the string sharpens focus and places these mass points in a coordinate grid. (e) Dragging one of the mass points and changing its position simultaneously reflects the change

in spring force acting on the mass point. (f) Dragging the slider changes the mass point under consideration, and this change is also reflected in the total force equation. The interactive system can be explored on a laptop/PC (with Google Chrome) using this link: [*https://ambargithub.github.io/manipulable-derivation-interactive/0.0_Outline.htm*](https://ambargithub.github.io/manipulable-derivation-interactive/0.0_Outline.htm)

5.3 Overall interaction with the system

Each participant's experience of the learning system involved interaction with 16 screens. The first two screens provided a general background, exposing participants to the performative framing of derivations and the five step sequence respectively. The next ten screens were specific, where participants interacted with interactive elements that allowed them to enact the 5-step sequence of a particular physics system. These screens typically consisted of three interaction elements (highlighted for the idealisation step in Figure 5.7). At the top was the progress bar, which indicated where each participant was in their learning journey. Arrows on the side allowed navigation, and arrows underneath the bar indicated direction of progress (Figure 5.7A). The right half of the screen had visual elements which underwent transformation as participants interacted with them (Figure 5.7B). For the first two steps, these elements had an iconic representational format. Later, symbolic format was fused with the iconic format in these elements. At the idealisation step shown in the figure, participants saw a guitar and a suspension bridge. Both these elements represented concrete examples of oscillatory motion. The left half of the screen had a textual and an interactive component. The text was aimed at supplementing the restructured teaching narrative. The interactive component consisted of a slider. Dragging the slider gradually faded the concrete properties of the visual elements, and exposed the underlying systematic pattern – the phenomenon of oscillation. The interactive components were present in various forms, including the form of a slider or the iconic elements on the right, which could be directly interacted with.



Building an ideal system

Stripping away reality to create the simplest active part

A guitar and a suspension bridge might seem like two very different objects.
But what is that common property which makes a guitar and a bridge similar ?

Drag the slider to isolate this common property !!

Figure 5.7 Elements on most screens of the derivation system.
(a) Progress bar with arrows to navigate between different steps in the system. (b) Visual elements which underwent change as the user interacted with enactive elements. (c) Textual presentation of narrative at each step. The slider in this step is used to idealise the two images and display the similarity between them.

Once the 5-step sequence was over, the last three screens provided a summary of the derivation sequence in general, and situated it in the larger framework of the scientific method. The theoretical track (lower hemisphere, Figure 8) summarised the process of derivation, where participants could drag the sliders and observe reality being gradually transformed into a mathematical equation. The experimental track (upper hemisphere, Figure 5.8) described the parallel transformation of reality in experiment design, which has its own steps. The teaching narrative highlighted the process of testing and revising the built model, by comparing the output of the equation model system with the output of the experiment model system. This narrative also supports the teaching of data fitting. However, this element was not included in this iteration of the design. We plan to include this component in a future iteration, where the system will be used for teaching in conjunction with laboratory tasks.

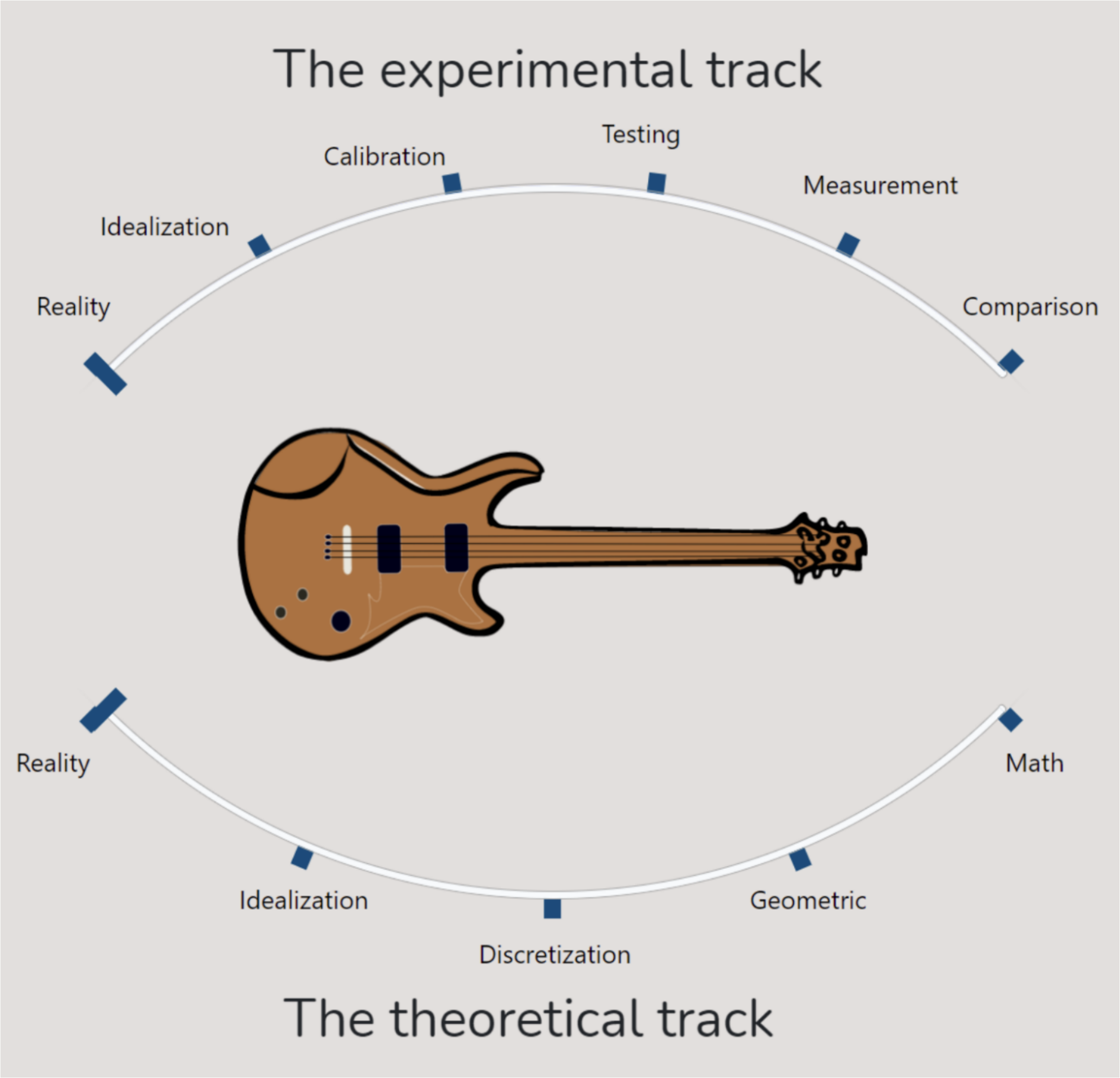


Figure 5.8 The relationship between model-building and the scientific method, outlined using a series of steps involved in the theoretical and experimental investigation tracks

The 5-step sequence reveals the complex cognitive structure of each step in a derivation, which is hidden in pedagogies based on the algorithmic approach. In particular, it shows how the student needs to transform the real-world system at each step, but keeping in mind the previous step and upcoming steps. For instance, when generating the idealisation, students need to shift back and forth between the real-world system and the idealised system, to establish the right mapping. This process is also constrained by the upcoming steps, as the idealisation needs to be structured in such a way that it can support later mathematization. This constraint leads to only geometric structures that are easy to represent in a coordinate space being chosen. In general, the process of building the model involves transitioning back and forth between the real-world system and the idealised/mathematical system, and intertwining both. Keeping all these steps running in short-term memory and imagination is very difficult. Minimally, each step in a derivation can be considered as having a dual and bistable cognitive structure, requiring students to think about both real-world aspects and mathematical aspects. To be able to do model-building (to solve open-ended problems), students need to acquire the ability to keep in mind – and transition smoothly between – these two cognitive states, and intertwine them systematically. Further, students also need to keep in mind the requirements of the given problem. The level of cognitive load involved in this process is very high, and this is one of the reasons why model-building is difficult. It becomes even more difficult when the systematic steps involved in model-building are unknown or unclear. By revealing the systematic steps, our system provides students with a minimal framework to start model-building. To become experts, and also to manage the cognitive load involved in model-building, students require a lot of practice in building models. Our studies with the interactive system did not provide such practice, so our results are very preliminary.

5.4 Implementation of the teaching study

Ten physics major students (three male, seven female), attending the first semester of a master’s degree in physics (after three years of undergraduate study), were recruited. As shown in Figure 5.9, each participant’s study was done in three parts (in online mode due to Coronavirus disease [Covid-19] pandemic), over a period of two days. Two types of data were collected from participants. Qualitative data (labelled ‘Talk data’ in figure) generated during the interviewer's interaction with the participants. And performance data, which evaluated their accuracy on various tasks.

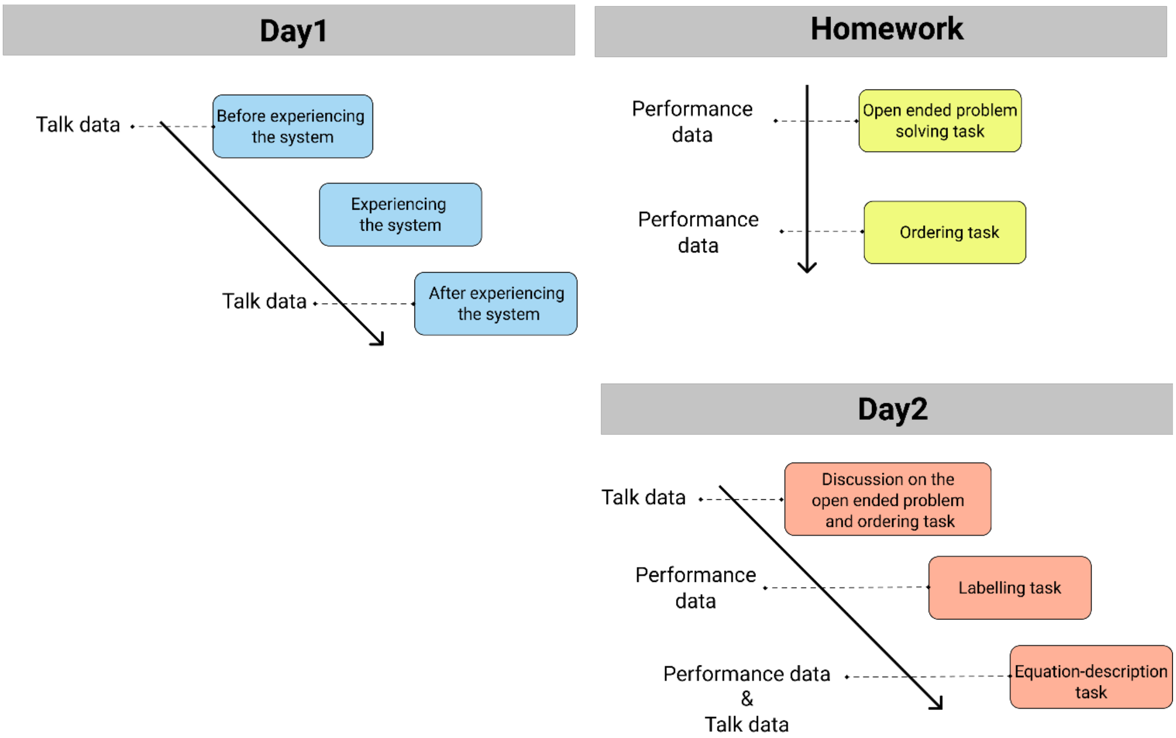
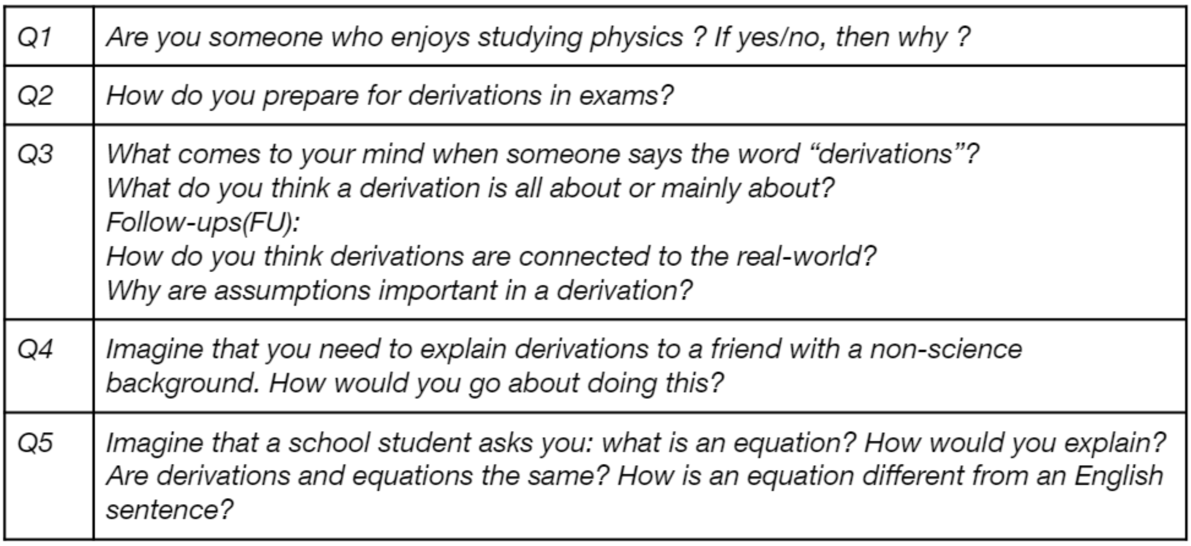


Figure 5.9 Parts in which each participant's study was conducted, along with the types of data collected.

Day 1 (in blue) shows the three stages of the study. This was followed by homework tasks (in yellow). On Day 3 (in orange), the student was first asked to discuss his reasoning behind the homework tasks. This was followed by two other tasks

On day 1, students were asked open-ended questions in a semi-structured format, before and after they experienced the derivation system. The physics expert ensured that the system was understood by each student. Figure 5.10 lists the questions that were asked before students experienced the system.



Q1	*Are you someone who enjoys studying physics ? If yes/no, then why ?*
Q2	*How do you prepare for derivations in exams?*
Q3	*What comes to your mind when someone says the word "derivations"?* *What do you think a derivation is all about or mainly about?* *Follow-ups(FU):* *How do you think derivations are connected to the real-world?* *Why are assumptions important in a derivation?*
Q4	*Imagine that you need to explain derivations to a friend with a non-science background. How would you go about doing this?*
Q5	*Imagine that a school student asks you: what is an equation? How would you explain? Are derivations and equations the same? How is an equation different from an English sentence?*

Figure 5.10 Questions asked by the physics expert before students experienced the system.

After experiencing the system, students were asked to *describe* how they thought the system related to their understanding of derivations. Secondly, they were asked how they would explain derivations and equations to a non-physics friend, to track the changes in their *understanding* about these key concepts. After this step, the homework tasks were explained. On Day 2, the homework tasks were discussed alongside two new tasks (labelling and equation-description). **For the purpose of this thesis, we analyse only the open-ended problem-solving task**. Afterwards, the researcher reflected back on the two-day experience with the student, and informally clarified any queries the students had about his/her responses on the tasks, and also the nature of the study.

5.5 Data analysis

Students' performance in the ordering, labelling, problem-solving and equation-matching tasks were first collated. After that, the interview data was transcribed for all the ten students. One student's (S10) interview responses data was found to be insufficient for analysis. The final data analysis was thus conducted for nine students in total. The transcribed data was then analysed for episodes of intertwining, both pre-intervention and post-intervention. This analysis is similar to data analysis approaches based on conceptual blending (Van den Eynde et al., 2020; 2023; Hu & Rebello, 2013; Odden, 2021). Our data analysis approach primarily involved identifying the episodes where students engaged in intertwining, and scoring those episodes on a High, Medium, Low scale. In the context of our project, intertwining is defined as the process in which a participant constructs explicit interlinkages between two or more conceptual components. For an excerpt to qualify as one involving intertwining, it had to fulfil two criteria. One, it should have two or more relevant conceptual components, and two, interlinkages between those components should be explicit. The criteria for a component to be considered relevant varied across different tasks, but the presence of interlinkage between the components remained a consistent indicator of an intertwining episode across all the analyses. The intertwining theme was chosen as the analytical framework because, as discussed earlier, the ability to intertwine the derivation steps, and related ERs, is central to the building of equations. This ability also indicates understanding of the component ERs.

The transcripts were read by two raters, and the task performance, themes for intertwining, as well as the ratings for each student, were arrived at through discussion. A third rater (the physics education researcher who did the teaching) independently rated the performance data, as well as the level of intertwining for each student, in the pre and post data. The two independent ratings were later compared, and any differences were resolved through discussion, to arrive at the final rating.

For each student, the day 1 pre-intervention data was analysed by following three steps: identification of intertwining episodes, thematic classification, and scoring. This process is captured by the funnel A in Figure 16. Components involving both abstract conceptual knowledge of physics and concrete scenarios were considered relevant for an intertwining episode. If the concepts being discussed were linked to modelling, this episode was classified as a *modelling* theme. If the discussion was on functional knowledge of physics or mathematics, it was classified as an *operational* theme. Each episode under these two themes was then scored as a High, Medium, or Low on intertwining.

Figure 13 lists representative quotes that were considered relevant for all the three steps. The yellow portion of each quote focuses on the abstract component, while the blue portion focuses on the concrete component. The quote in column one highlights interlinkages between the abstract concept of an ‘equation’ and the concrete scenario of a ‘pendulum in motion’. What links these two components is the notion of ‘equation as a function of two variables’, the relevant variables in this episode being angle and time. Next, these intertwining quotes, which exhibited componential and linkage characteristics, were classified thematically. Consider the modelling episode. This episode is classified as such because it discusses the abstract component of ‘idealisation’, by linking it to the concrete scenario of ‘frictionless surfaces’ as an idealised assumption.

The final step involved scoring the strength of intertwining. If an episode involved a strong elaboration of components as well as a strong interlinkage between them, it was scored High. However, if both elaboration and interlinkages were weak, the episode was scored low. This scoring criteria was true for intertwining episodes across all tasks. Figure 15 provides an overview of these criteria for all three scores.

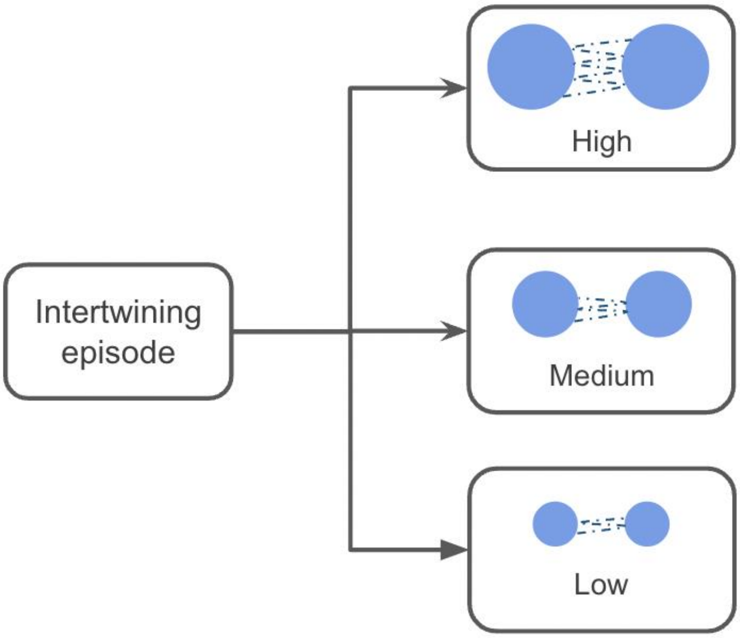


Figure 5.11 Scoring criteria for intertwining episodes.
Each intertwining episode is scored on the basis of elaboration within a component and interlinkages between components. Blue balls represent relevant components and their size represents the amount of elaboration. The number of dotted lines represents the strength of interlinkage between components. The components vary across tasks.

Consider the quote scored ‘High’ in Figure 17. It discusses links between the abstract concept of ‘idealisation’ in the concrete scenario of a ‘pendulum in motion’. What's central to the interlinking is the idea that equations describing ideal systems can be modified to account for real phenomena. This idea is mapped onto the concrete scenario of a pendulum, which in ideal circumstances doesn’t face air resistance, but in real circumstances does. This discussion was judged as meriting a high value. In contrast, an episode is scored low if both elaboration of components and interlinkages between them aren’t fleshed out clearly. The quote scored low in the figure only vaguely introduces both the concrete and abstract components. There is an attempt to map the two components, but it isn’t clear at all. Both components find mention of ‘solid state physics, but very weak linkages between them. Such episodes therefore get scored low.

The performance of students on all the tasks was also categorised as High, Medium or Low. The process for this is shown in the funnel B of Figure 12. Finally, students’ post-intervention reasoning, for their actions on each task, was also graded as High, Medium or Low. For the open-ended problem-solving task, derivation steps were considered a key component for the intertwining score. We also assessed if the students thought of equations as active systems, particularly machines.

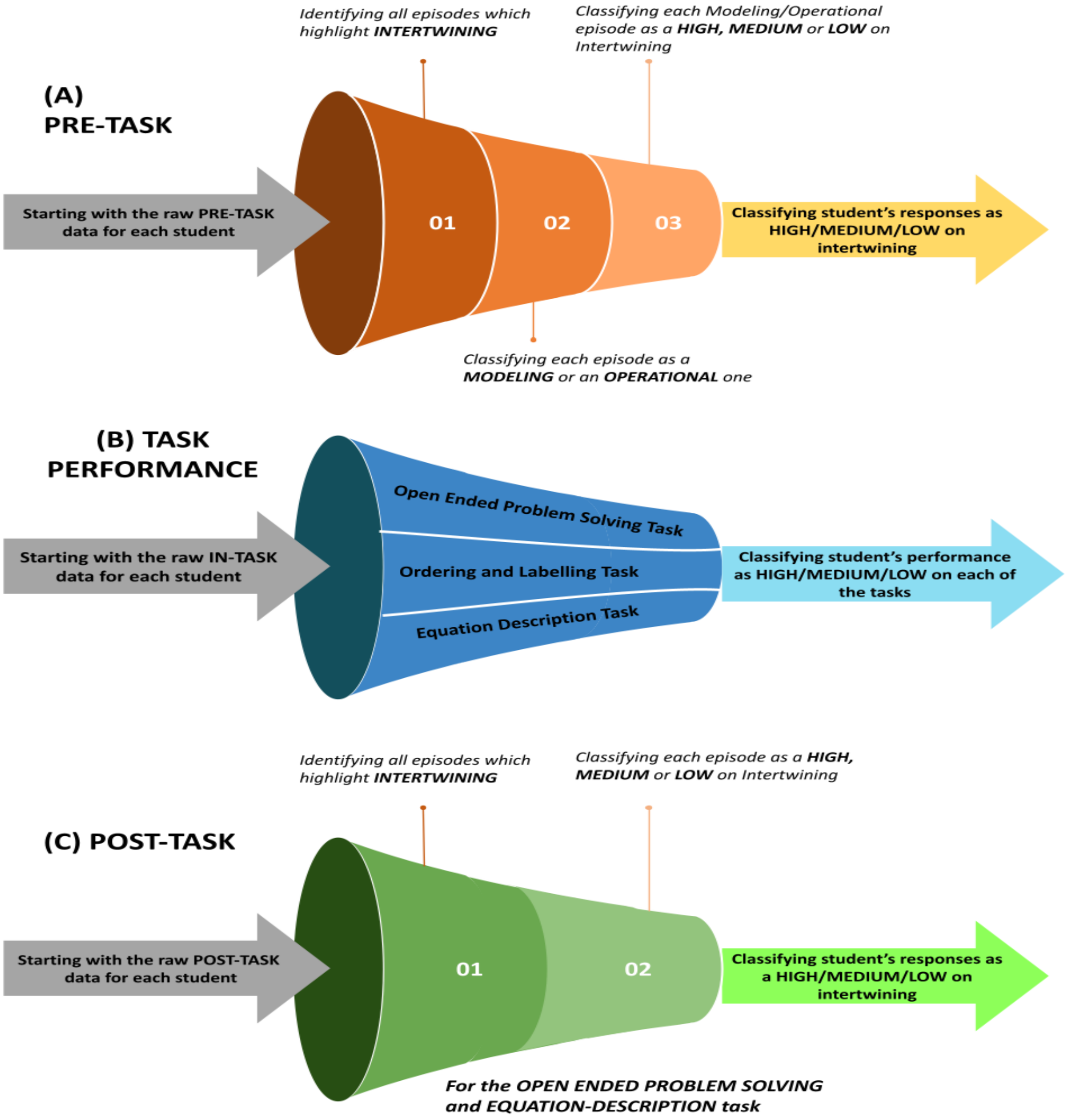
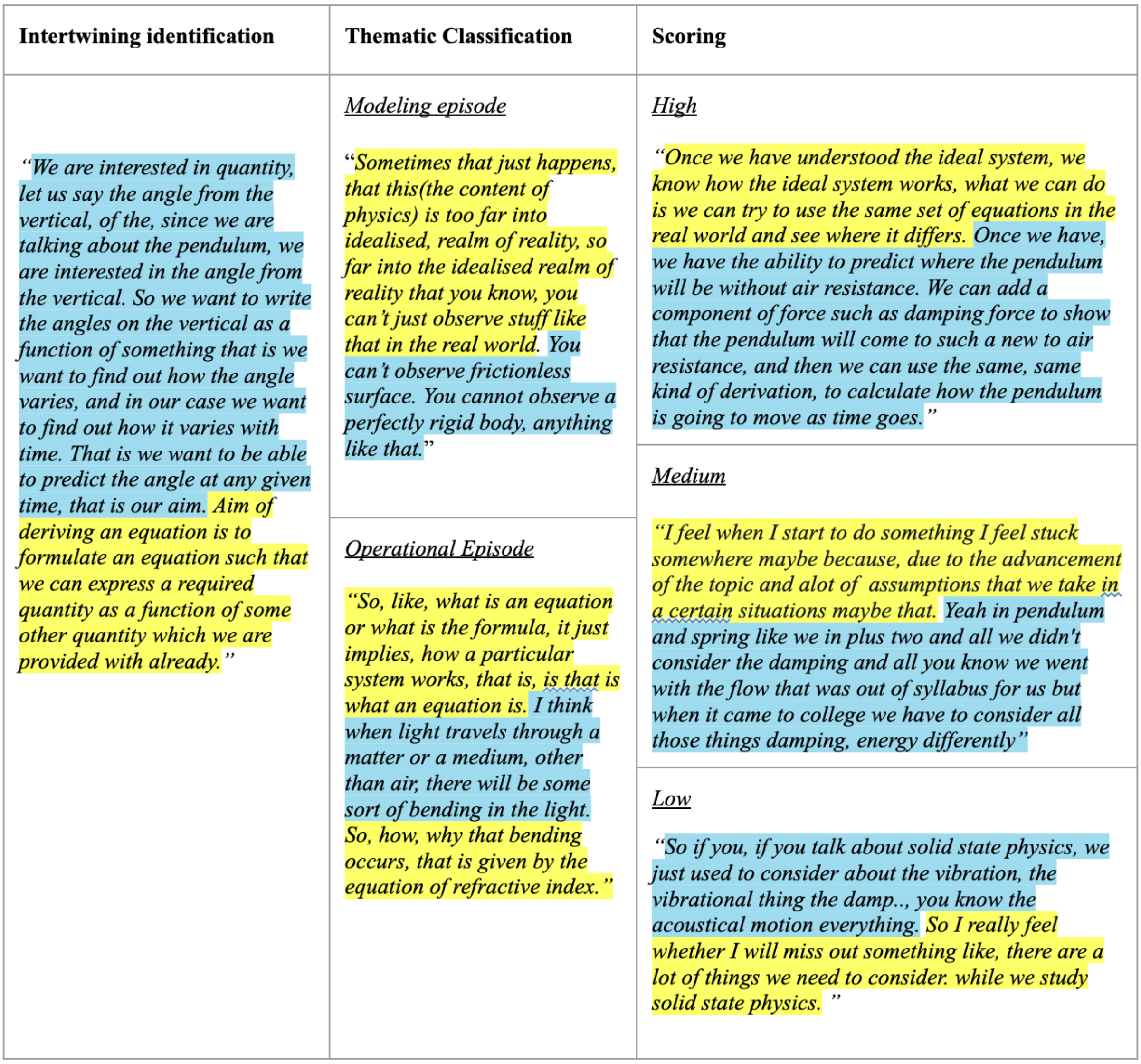


Figure 5.12 How data collected at all the three stages (pre, post, task) was analysed and classified.

(a) Pre-intervention data for each student is identified for intertwining, and classified as High/Medium/Low instances. (b) Students' performance on all the three action tasks is also classified as High/Medium/Low (c) Data for students' reasoning behind the tasks is classified as High/Medium/Low on intertwining



Intertwining identification	Thematic Classification	Scoring
"We are interested in quantity, let us say the angle from the vertical, of the, since we are talking about the pendulum, we are interested in the angle from the vertical. So we want to write the angles on the vertical as a function of something that is we want to find out how the angle varies, and in our case we want to find out how it varies with time. That is we want to be able to predict the angle at any given time, that is our aim. Aim of deriving an equation is to formulate an equation such that we can express a required quantity as a function of some other quantity which we are provided with already."	*<u>Modeling episode</u>* *"Sometimes that just happens, that this(the content of physics) is too far into idealised, realm of reality, so far into the idealised realm of reality that you know, you can't just observe stuff like that in the real world. You can't observe frictionless surface. You cannot observe a perfectly rigid body, anything like that."*	*<u>High</u>* *"Once we have understood the ideal system, we know how the ideal system works, what we can do is we can try to use the same set of equations in the real world and see where it differs. Once we have, we have the ability to predict where the pendulum will be without air resistance. We can add a component of force such as damping force to show that the pendulum will come to such a new to air resistance, and then we can use the same, same kind of derivation, to calculate how the pendulum is going to move as time goes."*
	<u>Operational Episode</u> *"So, like, what is an equation or what is the formula, it just implies, how a particular system works, that is, is that is what an equation is. I think when light travels through a matter or a medium, other than air, there will be some sort of bending in the light. So, how, why that bending occurs, that is given by the equation of refractive index."*	*<u>Medium</u>* *"I feel when I start to do something I feel stuck somewhere maybe because, due to the advancement of the topic and alot of assumptions that we take in a certain situations maybe that. Yeah in pendulum and spring like we in plus two and all we didn't consider the damping and all you know we went with the flow that was out of syllabus for us but when it came to college we have to consider all those things damping, energy differently"*
		<u>Low</u> *"So if you, if you talk about solid state physics, we just used to consider about the vibration, the vibrational thing the damp.., you know the acoustical motion everything. So I really feel whether I will miss out something like, there are a lot of things we need to consider. while we study solid state physics. "*

Figure 5.13 Representative quotes for all three stages (identification, classification, scoring) of analysis in pre-intervention data.

Every excerpt is identified for intertwining, then classified as an episode of modelling and operational themes, and finally categorised as a High, Medium or Low on intertwining. The concrete components involved in intertwining are highlighted in blue, and abstract components are highlighted in yellow.

5.6 Summary of Results

The results of this analysis are discussed below.

5.6.1 Open-Ended Problem-Solving Task

We found that students who had a low score on intertwining before experiencing the system exhibited low performance in solving the problem, as well as in intertwining different steps in the derivation. Students who had a High / Upper Medium (UM) score before experiencing the system were able to intertwine different derivation steps while solving the open-ended problem. In general, a student with a higher pre-score had a high performance and intertwining score, while a student with a lower pre-score had a low performance and intertwining score while solving the open-ended problem. S1 was not given the open-ended problem, as its design had not settled when he was interviewed. His classification is based on performance in the other tasks.

Table 5.1 and Table 5.2 report the performance on the task for each student, and a representative quote for high intertwining score. For students with a low intertwining score, there was very little data that indicated intertwining. The representative quote mentioned in Table 2 refers to the idealisation step in the system. This idealisation component is intertwined with the concrete scenario present in the open-ended problem. The linkage between the two components focuses on how the idealisation assumption is important for factoring in the role of oil in the motion of the pendulum.

PERFORMANCE

Student ID	Intertwining score before experiencing the system	Performance in the open-ended problem
S5	**H**	H
S1		H*
S7	**UM (Upper Medium)**	M
S2		M
S9	**LM (Lower Medium)**	H
S4		H
S6	**L**	L
S3		L
S8		L

INTERTWINING

Student ID	Intertwining score before experiencing the system	Intertwining score in the open-ended problem
S5	**H**	H
S1		H*
S7	**UM (Upper Medium)**	H
S2		H
S9	**LM (Lower Medium)**	L
S4		L
S6	**L**	L
S3		L
S8		L

Table 5.1 Students' performance on the open-ended problem.

Table on the left is each student's performance on the task, against their intertwining score before experiencing the system. Table on the right shows how well the students were able to intertwine different steps explained in the derivation system while solving the task.

Intertwining score	Representative quote
H	"I mean, the reality connecting to the physical model that we are studying is important. That is actually one good kickstart while solving any derivation or problem. If the assumptions aren't good, so, we might get in trouble while solving. I mean, I was referring the system yesterday and saw once again, how did it get step by step and how the real situation was and how we thought of getting the ideal, and what constraints, I mean, there is a possibility in this question. The oil question. Pendulum that I had in mind that if we neglect the oil entirely, we can take it in air but that wasn't a good assumption at all. We cannot do it because oil is really important. Otherwise, there's no buoyancy. And we have to consider that and that is an important assumption."

Table 5.2 Representative quote scored High on intertwining during the open-ended problem-solving task

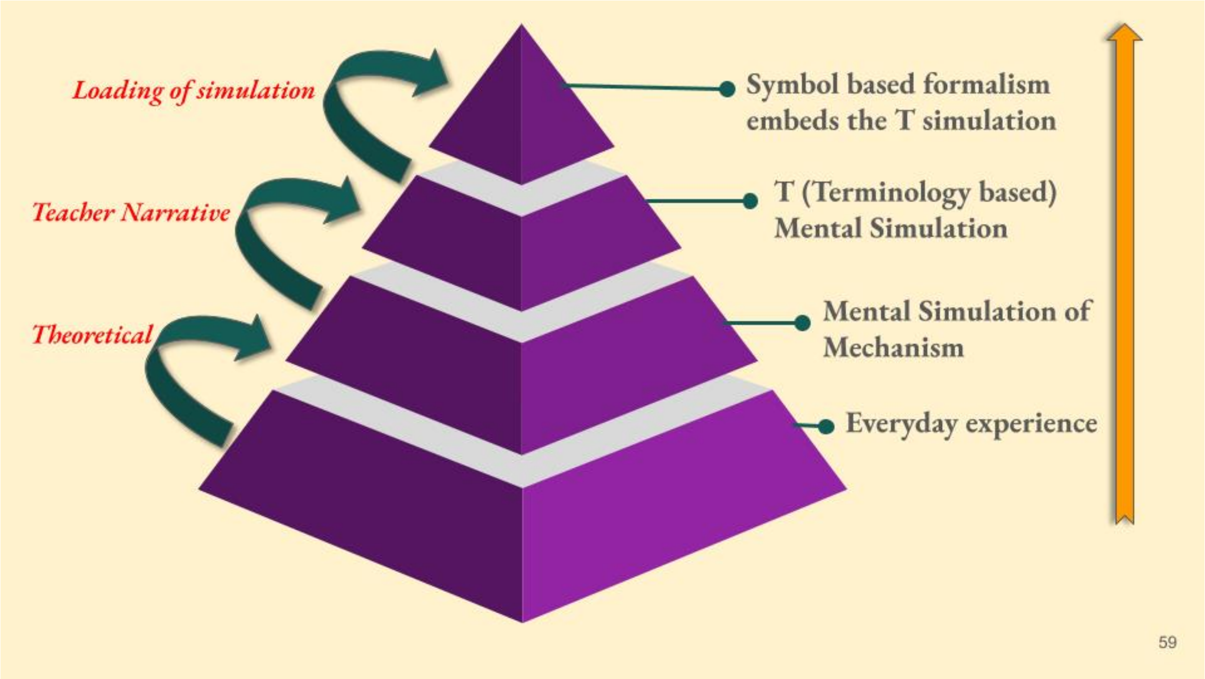


Figure 5.14 A schematic summarising how the PB account developed in the biology case gets extended to physics

In this figure the pyramid depicts a nested structure where each layer feeds into the layer on the top, starting from everyday experience and ending in symbol-based formalism. The base layer of everyday experiences gets activated as mental simulations by language, according to ESTL. As the simulation of experiences becomes less readily available for mechanism terms, teacher narratives reconfigure and bind these experiences in specific ways to the mechanism terms (to activate the mechanism models embedded in AL) using various enactive strategies. This is enunciated in the PB account. Increasing abstraction in AL – such as in the use of mathematical equations in the context of physics and other formal domains – requires the activation of mental simulations of both the PB terms as well as the symbol-based equations. This can be achieved through teacher narrative and embodied learning interfaces, which facilitate the loading of the PB (mental simulations) for the mechanism terms and also the loading of reality into the mathematical equations.

5.6.2 Experience of the system

In the post-intervention discussion, all students commented that they found the interactive system very useful, and it could contribute significantly towards a better understanding of the derivation process. Some comments from our study participants are shown in Table 8 below. One common theme (captured by St. 1 and St. 4 quotes) is that the system establishes an important "connection to the real world" rather than just focussing on numerical problems. These quotes indicate how our system can provide a meaningful alternative to the formalism's first approach [23], which overemphasises the use of symbols over concrete learning materials.

Another common theme is captured through the keywords ‘what is basically significant for study’. These words highlight the importance of the reality-to-idealisation transition in the system, which allows learners to refine their scope and focus on elements which are essential for understanding the phenomenon. In general, students' comments indicated that interacting with the system allowed them to generalise the inherent conceptual structure more widely, beyond the pendulum instance, indicating a change in their perspective on model-building.

	Representative quotes
St. 1	*"When we are using this way, connecting our real life to what we study, rather than just studying numerical problems. I think solving the problems will be much more easier because we can just analyse or construct a model in our own head, and then solve that problem rather than just, this is similar to that problem what we have studied in our class. Rather than thinking that way, we just create our own scenario in head and move on with our problem."*
St. 2	*"I think to me the biggest advantage is you know streamlining the thinking process, breaking down any phenomena, exactly identifying where you need to apply law, what law you need to apply, what part of the system is relevant to you and what part of the system is irrelevant. You know how it behaves, identifying how it behaves and then applying whatever law, you know that's not just for guitar or bridge, or for any other example you can also do the same thing."*
St. 3	*"Definitely visualisation helped a lot, in this particular case. And also, I had an option to work out different-different cases, like, when I had to drag the values and all, which is not possible in a conventional classroom situation."*
St. 4	*"Really good system. You know, breaking down a system into what is basically significant for study. I think in order to connect the real world with what we are studying in physics we have to always be able to do something like this."*

Table 5.3 Representative quotes describing students’ feedback on the derivation system

5.7 Study Discussion

Overall, the results of the data analysis indicate the following broad trends.

1) Participants with higher intertwining scores in the pre-intervention discussion performed better in the post-intervention tasks. They also had higher intertwining scores in the post-intervention discussion.
2) All participants could use the 5-step sequence labels to classify their ordering.
3) All participants simulated equations and scenarios in the equation-description matching task.
4) All participants found the system useful. It generated a different perspective for many students.
5) No participant indicated a perspective shift towards thinking of equations as machines. However, the high performers found the perspective interesting and novel.

Taken together, these results indicate that the novel teaching narrative based on the interactive system design was successful in generating a *moderate* change in students' understanding and perspective of derivations. The intervention was only *somewhat* successful in improving students' ability to solve open-ended problems. This success was *modulated* by students' pre-intervention ability to intertwine concepts. The system was not fully successful in moving participants' perspectives of derivations towards a prediction machine framing of equations.

Overall, the results show that the new teaching narrative – if used across many derivations, and many iterations – has the potential to generate a perspective change, and also the ability to successfully build equation models for open-ended problems. The current intervention was just a 45-minute one, and it was not expected to drastically change students' existing practice and understanding, which they had internalised across more than five years of learning physics, based on the currently dominant textbook-driven algorithmic approach. The moderate change in perspective indicated by the study, and the limited change in the ability to solve open-ended problems, are thus highly encouraging, from both application and theory points of view. We discuss some possible application extensions of these results below.

5.7.1 Pedagogy and design extensions

The convergence in the intertwining data suggests that the intertwining construct could be used as a general marker that teachers could use, after some training workshops, to track student progress in open-ended problem-solving. The finding that the intertwining skill in open-ended problems is modulated by existing skills suggests that focused remedial programs could be developed for students with low intertwining skills.

As most students showed skill in mentally simulating both equations and scenarios in the equation-description matching task, the process of intertwining seems to require training and effort much beyond this ability. The action elements used in the system could be one way to support this skill. In resource-limited learning environments, particularly in developing countries, teachers could be trained with the interactive system, and they could then try to replicate the active interactions in the system using their laptop, and then blackboard-based teaching, based on drawings and gestures.

As most students appreciated and remembered the 5-step sequence, and many used it in problem-solving, these steps, and the idea of a gradual loading of reality into equations, could be made a central element while teaching derivations and problem-solving. Further, the dual and bistable nature of the ERs at each step could be emphasised, which would help augment students' ability to intertwine the ERs involved.

The model of equations as prediction machines was appreciated by some students. Making this model part of the derivation teaching narrative would help students transition quickly and easily to computational modelling, where models 'run', and thus have a more explicit machinic nature (See Mashood et al. 2022 for a detailed discussion). Further, the view of equations as 'performative' entities (Salve, Upadhyay, Mashood & Chandrasekharan, 2024) could help advance students' understanding of the nature and function of equations in general.

We have successfully used the conceptualization and design of the system reported here as a *design pattern*, to develop five other similar derivation systems. These could be scaled further, to develop interactive textbooks, which could also include the interactive ordering and equation-description matching tasks. These could also be extended further to develop novel classroom evaluations. We are also working on extending this approach to model-building in chemistry, biology, and engineering.

5.8 Conclusion

We have outlined an approach to systematically develop novel teaching technologies for learning mathematical model-building in physics, restructuring existing textbook-centred teaching narratives. We illustrated this process using the problem of teaching physics learners the general cognitive capability of model-building. Here we extend the PB theoretical framework developed in the biology context to a physics model building context. A parallel is drawn between `stacking' of basic mechanisms to form complex mechanisms (in biology) and the `loading' of real world elements into equations (in physics). Further, we show how the process of building an equation can also be understood in performative terms.

The pedagogical implication of this performative account of physics model-building is that increasing abstraction in AL – such as in the building and use of mathematical equations in the context of physics and other formal domains – needs the activation of mental simulations of the PB terms, the symbol-based equations, and the process of building the equations. We show how this simulation process can be facilitated through a combination of novel teacher narratives and embodied learning interfaces, which together promote the formation of the PB (mental simulations) for the mechanism terms, equations, and also the building process, i.e the loading of reality into the mathematical equations.

Chapter 6: Attention in the mind's eye: Using the Navon attention task to track the way the grammatical structure of text passages modulates mental simulation of perspective

In this Chapter

Behavioural and neuroanatomical studies show that reading comprehension is based on mental simulation, as modality-specific sensorimotor representations and processes related to the meaning of the text are activated during reading. Supporting this simulation view of reading comprehension, cognitive semantics analyses show that changes in lexical and grammatical features are accompanied by changes in mental simulation. These findings have wide implications for education, particularly the learning of science, because the structuring of academic language (AL) text that describes scientific mechanisms can modulate students' simulations, and thus their comprehension. We hypothesised that AL texts with different linguistic structuring will alter students' mental simulations, particularly their perspectives, and this change can be tracked through its effect on attention. We conducted this study on a group of 35 students (18 Make and 17 Female). We report initial results from an ongoing exploratory study to test this hypothesis. We first changed the linguistic structuring of AL text – particularly nominalisation – to change the encoded perspective. We then tracked the effect of this change on the global and local perspectives of student mental simulations, using a divided attention task. Initial results show a trend where changes in the passage structure led to a local attention effect. We discuss the implications of this indicative result, and ongoing work to further examine this finding.

6.1 Exploring the Language, Simulation and Attention Interaction

The mental simulation generated by reading any text is affected by the content of the text, and also by the way language is structured in the text. Several studies (Liu & Bergen, 2016; Bergen et.al., 2007; Zwaan et.al., 2002) have characterised the ways in which the structural and dynamic features of a given text change mental simulations. The nature of this simulation would vary significantly between students, depending on their real-world experiences, reading comprehension, and attention. The detailed nature of the mental simulations generated by different text structures – particularly in relation to AL – remains an under-researched topic in ESTL. An understanding of the relation between language structure and the way a mental simulation progresses through reading, and the possible cognitive mechanisms modulating this connection – would contribute significantly to the design of new teacher training models. Here, we designed an empirical study to better understand this connection.

Both lexical and grammatical aspects of language have been shown to affect mental simulation. For instance, subject nouns and main verbs were found to trigger visual imagery, when used in literal sentences about real space (Bergen et.al., 2007). Zwaan et.al., (2002) show that the object orientation implied in sentences produces interference effects, when executing actions in orientations incompatible with those implied in the sentence. In cognitive semantics, grammatical elements are considered to constitute a fundamental conceptual structuring system (Talmy, 2000), and changes in the grammatical structure of sentences are shown to generate related changes in meaning. Supporting this view, Bergen & Wheeler (2010) showed that the grammatical aspects of sentences about hand movement affect their mental simulation. In this study, sentences about hand motion with a progressive aspect were shown to be simulated, compared to sentences similar in every other respect except having a perfect aspect. The progressive aspect is thought to foreground the internal structure of an event, whereas the perfect aspect highlights the end states. Also, people are able to simulate spatial location if the grammatical aspect of sentences is progressive, rather than perfect (Liu & Bergen, 2016). These studies indicate that grammatical structure alters the perspective of the mental simulation. Further, Talmy (2000) argues that changes in perspective (of the mental simulation), brought about by linguistic structuring, can lead to effects on attention.

These studies have significant implications for education – particularly science education – as academic language (AL) seeks to generate very specific and focused simulations, and this objective is achieved partly through the grammatical structuring of AL. For instance, nominalisation, which is considered a marker of AL (Halliday & Martin, 2003) is based on a type of linguistic restructuring where verbs and adjectives are converted into nouns. The studies reviewed above suggest that this linguistic structure could be working as a way to generate a specific perspective, where the action relationship between the interacting entities gains prominence, rather than the entities or the actions themselves.

6.2 An ESTL Approach to Characterise AL: the Case of Nominalization

Many analyses of AL consider nominalization as one of its key features (Halliday & Martin, 2003; Schleppegrell, 2001; Snow, 2010). Given the centrality of AL in science learning, this view suggests nominalization could be playing a crucial role in supporting the shift to mechanism models and a scientific worldview. The following examples illustrate the way nominalization turns EL expressions to AL

1. The ball moves towards the fence

The movement of the ball towards the fence

2. Chlorophyll absorbs light energy

Absorption of light energy by chlorophyll

3. Water molecules split into hydrogen and oxygen

The splitting of water molecules into hydrogen and oxygen

In general, nominalization does not add more information to the sentence, but generates a reframed version of existing content. Specifically, nominalization generates entity categories from active process categories. For instance, in (1), the process nature of “moving” in the verb phrase “The ball moves” is objectified in the nominal phrase as “movement.” This form of redescription has the effect of turning processes into reified concepts, which can then be treated as manipulable entities. According to Sfard (1991), nominalization plays such a reification role in the learning of mathematics concepts as well, as this process helps turn (mathematical) process categories, which are action-like, into manipulable (mathematical) objects. In her view, learners transition to such a systematic object-based understanding of processes across a long period, and this gradual development is constantly modified by experience. Sfard argues that such reification of processes into structural concepts makes the processes available for manipulation as objects. In the reification view, nominalization works as a form of "freezing" of active processes, which turns them into entities. From the ESTL perspective, reading and understanding the nominalized AL sentence would require correctly simulating/imagining the "frozen" entities and their dynamics, which are encoded in the sentence. Compared to the EL sentences, this simulation process would be different in nominalized sentences. Since nominalization does not change the information content of the sentence, the key difference in the mental simulation of AL would be the way nominalization modulates the mental simulation of the sentence. One possible modulation could be the different ways in which nominalization helps "tune" the reader's attention to different aspects of the simulation, altering her perspective of the process encoded by the sentence. This difference in tuning, over long periods of reading and simulating AL, gradually leads learners to an internalisation of a new stance towards the world. In particular, the new stance would involve characterising and analysing processes in the world as entities, which is a critical component of the scientific worldview. For instance, a student reading [1: A ball moves from point A to B] would run a mental simulation where attention is primarily focused on the ball, and the moving of a prototypical ball would be simulated. However, when the sentence is rewritten as a nominal phrase [2: The movement of the ball from A to B], the attention shifts to the movement, but the movement is now treated as a property of the ball. The simulation of the movement in this case involves a certain distancing of the observer from the movement (compared to 1).

The framing of [1] makes the moving ball more salient to attention, and thus more available for simulation, compared to [2], where movement becomes objectified in the nominal phrase, and thus less available for simulation. Nominalization thus changes the "tuning" of the reader's "attention polygon" (the topological distribution of attention) while reading a sentence. Supporting this attention topology view, studies show that linguistic operators (such as modals—like can, may, must, should, ought) modulate attention in everyday language (Talmy, 2007). Recent studies show that the aspect feature of grammar (such as perfective, imperfective, progressive) also interacts with the content of the mental simulation (Bergen & Wheeler, 2010). These features (modals, aspect) are deployed extensively to navigate social and psychological domains (Talmy, 2007). This is typically an advanced use of language, where the role of language is closer to that of a manipulative tool (pragmatics), which is different from its use as a medium for description and communication (semantics). Such linguistic manipulation of mental simulations could thus be considered a marker of language expertise. Extending this inference, and also the above studies, to the practice of science, experts in different scientific domains should be able to deploy attention differently, compared to novices. Supporting this view, studies of science experts show that gaining representational competence leads to significant changes in eye movements and related visual attention (Pande & Chandrasekharan, 2017, 2022). To test the above hypothesis (that linguistic operators involved in AL modulate attention topologies), we have developed and run some preliminary investigations, using the way nominalization reshapes the reader's default orientation and perspective. As an example, consider the nuanced nature of causality in the following sentences:

1) The ball hits the stack of cards and they fall.

2) The hitting of the ball makes the stack of cards fall.

Statement (1) depicts one view of the interaction between two entities, wherein one entity acts on the other. Here, the acting entity, i.e. the ball is foregrounded in attention. In the nominalized form in (2), the focus of attention is shifted to the action element of the ball (which is now separated from the ball), and its relationship to the falling of the cards is emphasised, while the ball and the cards are pushed to the background. The change in the sentence structure, generated by nominalization, alters the reader's perspective of viewing the event in her mind's eye, even though the figure and ground relation between the ball and the stack of cards remains the same (Talmy, 2000). The event structure in (2) is relatively difficult to simulate, compared to (1), because the hitting action is detached and foregrounded, and it then needs to be connected to the falling of the cards, in a Lego-like structure, rather than as an interaction between the ball and the cards. Since such restructuring is a significant component of AL, this analysis suggests that the transition to AL leads to mental simulations where the state of the world is seen from the perspective of the entity, rather than from the agent and the process, which are more the focus in EL sentences. Further, in AL, the nouns used are generally dense concepts with nested conceptual structure embedded within them (stomata, oxidation, carbon dioxide, etc.). This dense structure would also hinder the mental simulation of dynamics, because these dense concepts themselves need to be simulated, as they are part of the created event structure. More broadly, the two processes discussed above—the tuning and reshaping of attention and perspective—could be understood as a way of developing a new kind of entity-centred simulation ability. The key theoretical insight from this attention-reshaping view of nominalization is the way the new simulation process is modulated—and promoted—by linguistic operators – such as passive voice and propositions – which are critical components of nominalized sentences. To study such modulation of attention and perspective, we developed a preliminary study (see Salve et al, 2023), where we modified the textbook AL passages systematically. Specifically, we edited the text to bring the object to the foreground, so that the interaction of agents is more apparent, and easier to mentally simulate. This process only alters the perspective, as the edits did not change the dense conceptual structure of nouns. The following edits were made in the passage:

- Passive voice was turned to active voice, wherever possible.
- The initial focus was shifted to the object elements, and the interactions they generate, rather than the process elements (which are often nominalized in AL).

We then used a standard divided attention task (The Navon Letter task) as a probe, to examine whether reading these passages led to any systematic changes in attention. The results indicate a trend, where the systematic change in the structure of the textbook passage has a systematic effect on the post-reading attentional state of students. Specifically, attention shifted from a local attentional state for the original textbook passage (AL) to a global attentional state for the modified passage (closer to EL). This transition indicates that the change in the structure of AL, particularly nominalization, has a modulating effect on attention. In the passages where the language was restructured (modified passage), the nominalization structure was removed, and passive voice was converted to active voice. The observation of a global attentional state after this change provides an indication that the perspective of viewing the mental simulation (in the mind's eye) varies with the linguistic structuring of sentences in the passage. Such modulation of the attention topology would be further advanced by the inclusion of technical terms, which are loaded with specific processes.

6.3 Participants, Task and Materials

Our sample comprised 18 female and 17 male high school students (N = 35), who were enrolled in grade 9. In this sample, 65% of students self-reported that they could read English well, while 35% considered their English reading ability to be medium. 62% of the participants reported that they could understand a sample text written in English well, while 38% evaluated their English comprehension ability as medium. The majority of the participants (86%) reported that they were taught mostly in English, but that their teachers would often resort to explanations in the local language as well.

6.4 Reading Task

We selected 3 passages from biology textbooks (grades 9 and 10). One described the structure and function of the Golgi apparatus, another explained photosynthesis, and the third one ecological succession. These passages were 6 sentences long (on average), and were selected because they described a scientific mechanism. In the context of our study, 'mechanism' refers to either the mechanics of a biological or anatomical structure (e.g., Golgi apparatus), or to the causal explanations of a biological or physiological phenomenon and/or process (e.g., ecological succession) (Nicholson, 2012).

According to the ESTL, reading any passage outlining a mechanism generates a simulation. This process involves a distribution of attention, because, to generate the simulation, each element that is read needs to be processed in relation to other elements that are encountered. The attention distribution would vary with different language structures, which organise the text elements differently. For textbook passages, the linguistic structuring is based on AL features, such as nominalization. The event structure of the dynamic mechanism, which needs to be generated from the passage structure, would be difficult to build (and thus understand) in the AL case, because AL sequences start with the detached action, rather than the object. This structure prioritises a detached action perspective, and thus an object-like treatment of action (nominalisation). The action/process part of the mechanism is foregrounded in this structure, pushing the interaction between the entities to the background. Consider the following example used earlier:

1) The ball hits the stack of cards and they fall.

2) The hitting of the ball makes the stack of cards fall.

The event structure in 2 is relatively difficult to simulate, compared to 1, because the hitting action is detached and foregrounded, and it then needs to be connected to the falling of the cards, in a Lego-like structure, rather than as an interaction between the ball and the cards. In AL, the nouns used are generally dense concepts with nested conceptual structure embedded within them (stomata, oxidation, carbon dioxide etc.). This dense structure would also hinder the mental simulation of dynamics, because these dense concepts themselves need to be simulated, as they are part of the created event structure.

To generate the experiment condition, we modified the textbook AL passages using the following rationale. We edited the text to bring the object to the foreground, so that the interaction of agents is more apparent, and easier to mentally simulate. This process only alters the perspective. The edit did not change the dense conceptual structure of nouns. The following edits were made in the passage:

- Passive voice was turned to active voice, wherever possible
- We shifted the initial focus to the object elements, and the interactions they generate, rather than the process elements (which are often nominalised in AL).

This process yielded 3 unmodified passages. A sample textbook passage and the modified passage are below.

Sample A (Textbook Passage)

An important characteristic of all communities is that their composition and structure constantly change in response to the changing environmental conditions. This change is orderly and sequential, parallel with the changes in the physical environment. These changes lead finally to a community that is in near equilibrium with the environment and that is called a *climax community. The gradual and fairly predictable change in the species composition of a given area is called ecological succession. During succession some species colonise an area and their population become more numerous whereas populations of other species decline and even disappear.*

Sample B (Modified Passage)

The way all communities are composed and structured constantly changes as environmental conditions change. This is an important characteristic of all communities. This change occurs in an order and a sequence, as the physical environment changes. A community that is in near equilibrium with the environment is finally formed due to these changes. It is called a climax community. The species composition of a given area changes gradually and in a fairly predictable way, this is called ecological succession. Some species colonise an area during succession and their population become more numerous whereas populations of other species decline and even disappear.

In the study, the time spent on reading the passage was recorded for every participant.

6.5 Divided Attention Task

We used a letter-identification task comprising a set of 14 Navon figures, where each figure contained a big (global letter, say H) made up of small (local letters, say L) in a 5 X 5 matrix. A global letter measured 4.7 cm in height and 4.1 cm in width, while a local letter measured 0.7 cm in height and 0.6 cm in width. In this task, letters E and H were the target letters that the participants were required to identify. All Navon figures were incongruent, implying that the target letters to be identified – E and H – were only presented at the global level (i.e., H/L, H/T, H/F, E/L, E/T, E/L) or the local level (i.e., F/E, T/E, L/E, F/H, T/H, L/H), but never simultaneously congruent at the global and local levels (i.e., the global/local letters could never be E/E or H/H). Upon presentation of the Navon figure, participants were required to respond via a key-press (key z for letter H, key m for letter E) if the presented image had H or E, either at the global or the local level. All Navon trials were presented in a random order, and participants' reaction times (RTs) and accuracy data were recorded.

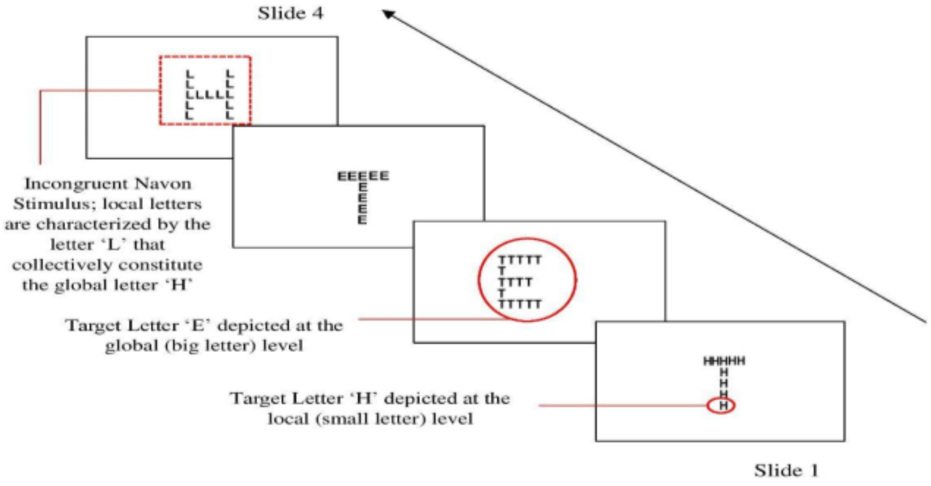


Figure 6.1: Schematic of the trial sequence of the Global Local Attention task

6.5.1 Experimental Design and Procedure

To determine the effects of linguistic restructuring on participants' attentional states, the study employed a mixed repeated measures design, with the following factorial structure: 2 (between subject factor: nature of passage- textbook, modified) X 2 (within subject factor: target letter type-local, global) X 2 (within subject factor: test sessions- pretest, post-test). All participants were administered the Navon task pre and post the reading comprehension task (the intervention). Participants were randomly assigned to either the textbook passage (non-modified, control condition) or the modified passage (experimental condition), respectively. All testing was conducted in-person, in a single session, on a 15.6-inch LED HP laptop screen. Both task stimuli and task sequence were pilot-tested with a sample of ten 9th grade students before they were implemented in the study. Consent was provided by all participating students before the experiment. Each student was exposed to 14 Navon task trials in the pre and post-tests. The pre and post-tests contained 7 local and 7 global trails, randomly assigned.

6.5.2 Analysis

We calculated the mean Global-Local RT bias (GLB) for each student. If participants respond faster to the local trials, they have a local bias. If they respond faster to global trials, they have a global bias. GLB is the difference between the mean global reaction times (GT) and the mean local reaction time (LT), across trials.

$GLB = GT - LT$

If the GLB is negative, it indicates a global bias i.e., on average the reaction to global stimuli was faster than the local stimuli. Similarly, a positive GLB indicates a local bias i.e., on average the reaction to local stimuli was faster than the global stimuli.

6.5.3 Results

The bar plot in figure 2 compares participants' performance on the divided attention task in the pre- test and post- test conditions, as well as between control (textbook passage) and experimental (modified passage) conditions. The yellow-coloured bars depict participants' (mean) LT and the blue-coloured ones, their (mean) GT.

In the control condition, the (mean) LT for participants in the pretest session was found to be higher than their (mean) LT in the post-test session, However, their (mean) GT in the pretest session was found to be lower than their (mean) GT in the post-test session. This trend suggests that post intervention (the unmodified, textbook passage), participants in the control condition reacted faster to the local-level (Navon) stimuli than the global-level (Navon) stimuli. This indicates their local bias.

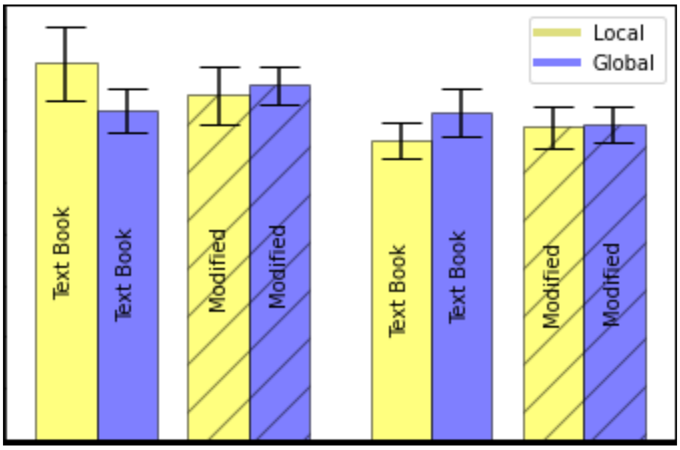
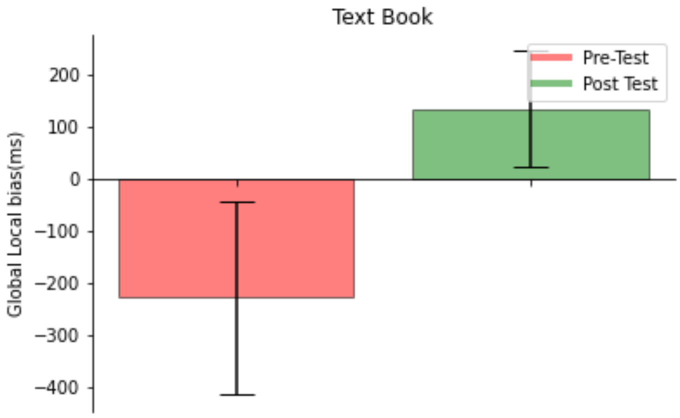


Figure 6.2: Bar plot depicting reaction time results from Global Local Task
The error bar indicates standard error of mean (SEM)

In the experimental condition, on the other hand, the (mean) LT for participants in the pretest session was found to be higher than their (mean) LT in the post-test session. However, their (mean) GT in the pretest session was found to be modestly lower than their GT in the post-test session. This trend suggests that post-intervention (the modified passage), participants in the experimental condition reacted faster to global-level (Navon) stimuli. This indicates their global bias.

6.5.3.1 Overall Global-Local Bias (GLB)

The mean GLB between the pre-test and post-test was compared for both the text-book passage and the modified passage for all the students. A negative value of the (-GLB) indicates a global bias in the pre-test, whereas a +GLB indicates a local bias in the post-test. The transition from local bias to global bias after administering the textbook passage indicates that the text book passage induced a local bias among the students. In the case of the modified passage, the students started with a local bias, which reduced after the administration of the modified passage. This trend indicates that students started responding faster to the global stimuli on reading the modified passage.



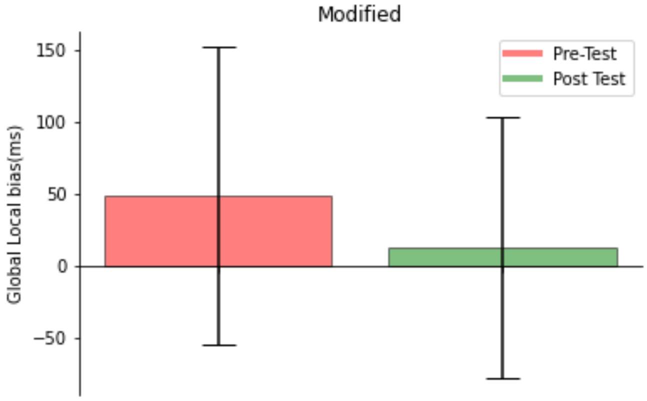


Figure 6.3: Comparison of GLB between the textbook passage and the modified passage

This plot is a comparison of the mean GLB between the textbook passage group (pre-test: 95% CI (-623.79, 166.53) post-test: 95% CI (-100.47, 370.49)) and the modified passage group (pre-test 95% CI (-166.57, 264.41) post-test 95% CI (-176.86, 202.98)). The pink bar indicates GLB in pre-test conditions whereas the green bar indicates GLB in post-test conditions

6.5.3.2 Comparison of GLB across gender

To check for within sample variability, a comparison of GLB across gender (female/male) was made.

Females: The textbook passage group showed global bias in the pre-test trials for female participants (indicated by the negative value of GLB), which changed to local bias (indicated by the positive value of GLB) on administration of the textbook passage (pre-test: 95% CI (-873.04, 229.70) , post-test: 95% CI (113.59, 523.47)). This trend is similar to the overall trend, where a similar change was observed. In the modified passage group, (pre-test: 95% CI (-238.49, 307.53) post-test: 95% CI (-254.25, 176.11)) showed a local bias, which changed to global bias after administration of the modified passage.

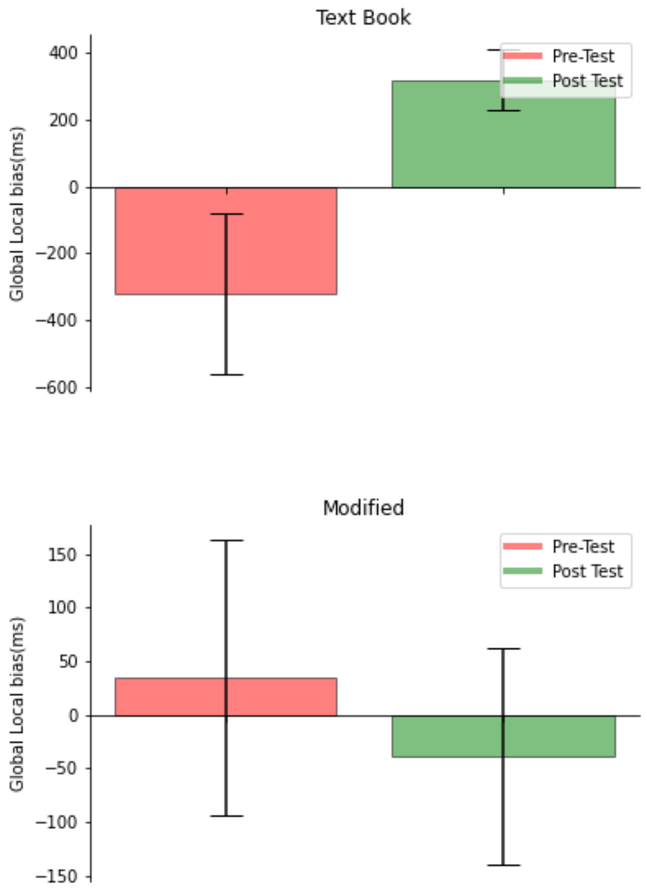


Figure 6.4: A plot comparing the mean GLB across gender
In this plot the mean GLB for the textbook passage and the modified passage conditions are compared across the pre and post-test conditions for the female sample

Males: The textbook passage group (pre-test: 95% CI (842.38, 594.45) post-test: 95% CI (-534.07, 391.19)) showed global bias in the pre-test trials for males (indicated by the negative value of GLB), which decreased on administration of the textbook passage. This trend is compatible with the overall trend, where administration of the textbook passage had induced a local bias i.e., decreased the mean RT to local stimulus. In the modified passage group (pre-test: 95% CI (-142.94, 355.99), post-test: 95% CI (-405.09, 848.250)) students in the pre-test showed a local bias which further increased after administration of the modified passage.

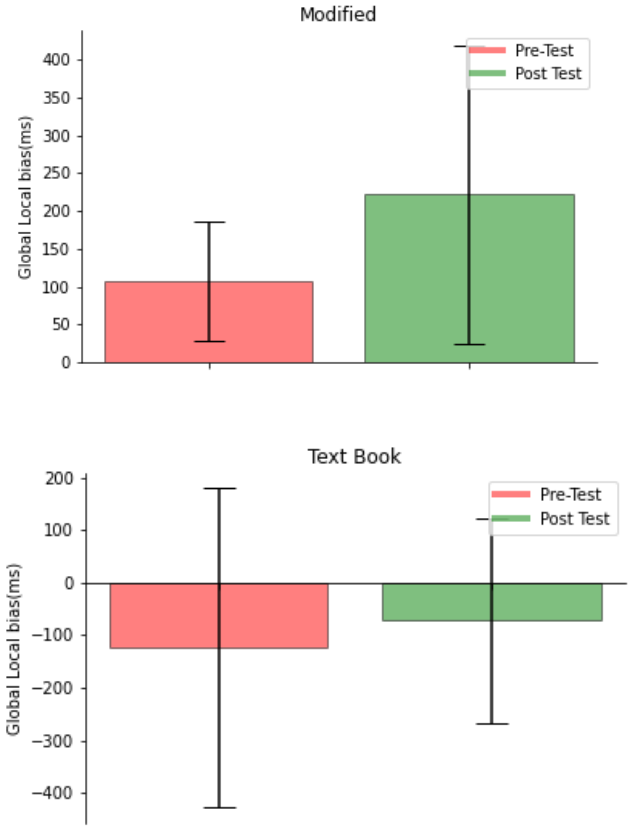


Figure 6.5: A plot comparing the mean GLB across the pre-test and post-test conditions

In this plot the mean GLB for the textbook passage and the modified passage conditions are compared across the pre and post-test conditions for the male sample

6.6 Discussion

We explored whether changing the linguistic structure of textbook passages of scientific mechanisms would modulate attention, via changes in the mental simulation associated with the different passage structures. The attentional states that we examined in this study are global attention and local attention. The results we report here indicate a trend, where the systematic change in the structure of the textbook passage has a systematic effect on the attentional state of students. Specifically, attention shifted from a local attentional state for the textbook passage (Al) to a global attentional state for the modified passage. This transition indicates that the change in the structure of AL, particularly nominalisation, has a modulating effect on attention. In the passages where the language was restructured (modified passage), the nominalisation structure was removed, and passive voice was converted to active voice. The observation of a global attentional state after this change provides an indication that the perspective of viewing the mental simulation (in the mind's eye) varies with the linguistic structuring of sentences in the passage.

When the results were analysed across gender, the female population showed a pattern similar to the overall trend (modified passage inducing a global attentional state). The trend was found to be reversed in the case of males (n=4). This difference could be due to the low sample size. These trends in the present study could be verified and further validated by an increase in sample size. We are currently working on extending the analysis to different kinds of mechanisms in biology textbooks.

Based on past studies, and also the way fiction authors structure their passages for different effects in the reader, there is reason to believe that change in both the lexical and grammatical (structural) features of language relates to change in mental simulation. Though the connection between attentional states and mental simulation has not been empirically explored, studies indicate that what is attended to in a mental simulation is related to linguistic structures such as grammatical aspect. The present study presents an initial foray into exploring the way attention shifts in the mind's eye during reading, based on different linguistic structures, to generate different kinds of mental simulations. The trends reported here are only indicative. However, the study illustrates a possible avenue to explore the way the mind's eye responds to language structure, and possible ways to use this effect to design passage structures, particularly for science education.

The bar plot in figure 2 compares participants' performance on the divided attention task in the pre- and post- test conditions, as well as between control (textbook passage) and experimental (modified passage) conditions. The yellow-coloured bars depict participants' (mean) LT and the blue-coloured ones, their (mean) GT.

In the control condition, the (mean) LT for participants in the pretest session was found to be higher than their (mean) LT in the post-test session, However, their (mean) GT in the pretest session was found to be lower than their (mean) GT in the post-test session. This trend suggests that post intervention (the unmodified, textbook passage), participants in the control condition reacted faster to the local-level (Navon) stimuli than the global-level (Navon) stimuli. This indicates their local bias.

In the experimental condition, on the other hand, the (mean) LT for participants in the pretest session was found to be higher than their (mean) LT in the post-test session. However, their (mean) GT in the pretest session was found to be modestly lower than their GT in the post-test session. This trend suggests that post-intervention (the modified passage), participants in the experimental condition reacted faster to global-level (Navon) stimuli. This indicates their global bias.

Although the results are not conclusive, there is indicative evidence that nominalisation may alter the nature of the simulation by altering the attentional states. It suggests that passages with nominalised phrases distributed attention locally while those without them showed a global bias. A more structured and detailed study, designed taking inputs from this study, could help understand these connections better.

Chapter 7: Concluding Remarks: Summary of Key Findings, Educational Implications, Limitations and Future Directions

In this Chapter:

We provide a brief summary of the important findings from the three studies. Extending the findings, we propose possible implications of the results e for different dimensions of education. First, the work reported in this thesis can improve the design of teacher training and educational technology . It can also inform policy decisions that seek to address the AL problem. The studies we report have several limitations, particularly related to sample size and implementation. These limitations are partly because of the execution of the study during the pandemic. We propose possible extensions that can enhance the indicative results we report from the present studies.

7.1 Introduction

The research reported in this thesis is driven by the central question: **How do science teachers' classroom narratives build dynamic models in students' minds?** To answer this research question, we collected classroom observation data. Building on the ESTL and distributed cognition theory, we analysed the data and proposed the theoretical construct of the Performative Bundle (PB). We then extended the account of PB developed in biology to the discipline of physics, analysing a physics derivation using the performative bundle construct. This analysis brought out the need for an additional theoretical framework to account for the physics disciplinary knowledge. It also brought to the foreground the disciplinary differences in the nature of scientific knowledge. In a third study, we explored the connection between the structure of AL and the nature of embodied simulation. Here we explored the effect of different linguistic structures on the attention distribution of learners. Below we provide a brief summary of the important findings from the studies.

7.2 A brief summary of the findings

A brief summary of the important findings across the three studies is given below

7.2.1 The construct of the performative bundle

The performative bundle emerged as a theoretical construct to account for the different case studies, which captured the dynamic interactions between the teacher and the student as the teacher explained mechanism models.

Some of the different dimensions of the Performative Bundle construct are below:

- **Connects Abstract Mechanisms to Real-World Experiences:** Mechanisms like photosynthesis are highly abstract and often beyond the direct experience of learners. The PB is the way teachers "seed" these abstract ideas into students' minds, by systematically connecting them with everyday experiences that students are familiar with. The 'performative' aspect of the PB, and the grounding of this aspect in ESTL, provides a systematic account of how students replicate the mechanism, and thus understand and internalise it, from the teacher's enaction of the mechanism in the classroom.
- **Dynamic Learning Process:** Unlike the view of 'transfer' of knowledge, the PB provides a way to understand dynamic processes in the classroom, particularly how teachers adjust their strategies based on student responses, classroom discussions, and feedback. This adaptability is key in helping students build and revise their mechanism models as new layers of the model are introduced.

The Performative Bundle construct captures a vital pedagogical tool that integrates narratives, gestures, analogies, visual aids, and language, into a cohesive bundle for teaching scientific mechanisms. Using the PB construct, we can analyse the way teachers bridge the gap between students' everyday experiences and the abstract models of scientific phenomena, and also the external performance of the teacher and the internal conceptual change in learners, thus making difficult concepts like photosynthesis accessible and meaningful.

7.2.2 Performative Bundle Extension to Physics

This study provides an extended analysis of performative bundling in the context of physics education, through the development of an enactive approach to teaching physics derivations. Key findings from the study include:

7.2.2.1 Equation as Performative entities

The study adapts the performative bundle (PB) construct, originally developed to capture the process of teaching biological mechanism, to physics education. In this new context, equations and derivations are viewed as **performative entities**—active structures that *enact* physical changes. This novel view presents a new way to understand equations, compared to traditional views of equations as static symbolic entities.

7.2.2.2 Model-Building in Physics

The study emphasises that physics derivations, often presented as a sequence of formal steps, should be understood as a **dynamics-laden sequential process, which** systematically "loading reality" into symbols, i.e. equations. This characterisation of formal models, and their building, significantly extends the building of **mechanism models** in biology. Further, this view also helps unify two other theoretical approaches to analyse modeling – conceptual blending and concreteness fading.

7.2.2.3 Interactive Teaching System

A key contribution of the physics study is the development of an interactive system that seeks to enhance students' understanding of derivations. This system embeds and encourages a performative approach to understand model-building, allowing students to actively engage with derivations through manipulations and simulations. The interactive derivation system is based on five discrete steps (e.g., reality, idealisation, discretisation, geometric structuring and algebraic manipulation), organised in a tapering funnel-like structure, which guides students through the process of transforming complex real-world phenomena into simple mathematical equations that enact key aspects of the reality.

7.2.2.4 Improved Student Understanding

The study found that students who engaged with this interactive system demonstrated a deeper understanding of the derivation process, as measured through tasks that assessed their ability to **intertwine** abstract concepts with concrete scenarios. The interactive system also helped students transition from the view of derivations as algorithmic problem-solving to derivations as model-building, and encouraged the shift toward seeing equations as **active prediction**

machines.

7.2.3 Studying the relation between linguistic structure and mental simulation, using an attention task

In the third study we investigate the effect of linguistic structuring, specifically nominalization, on mental simulations, using the performance in an attention task during reading comprehension of scientific texts. The study explores how academic language (AL) structures, particularly nominalization, affect the mental simulations that readers generate while reading scientific texts. Nominalization, which converts actions (verbs) into abstract nouns, shifts the reader's focus from entities (e.g., objects) to processes or actions, altering how the simulation is experienced.

7.2.3.1 Attention Shift

By manipulating the grammatical structure of textbook passages (from passive to active voice, and from nominalized to non-nominalized forms), we found that different text structures led to distinct attentional biases. Readers showed a local attentional bias when reading nominalized, textbook-style passages but a global attentional bias after reading modified, active-voice passages.

7.2.3.2 Navon Attention Task Results

Using participant performance in the Navon attention task as measure, the study found that participants exposed to textbook passages reacted faster to local-level stimuli, indicating a local bias. In contrast, those who read the modified passages (with active voice and de-nominalized sentences) showed faster responses to global-level stimuli, indicating a global bias in attention. This indicates that the linguistic structuring of passages influences how students allocate attention during reading.

7.2.3.3 Gender Differences

The study also noted gender differences in attentional shifts. Female participants' performance showed an overall trend, with modified passages inducing a **global attentional bias**, while male participants displayed more variability in attentional response. This effect could be potentially due to the small sample size.

7.3 Educational Implications

Below we discuss some of the implications of these findings on different aspects of education.

7.3.1 Teacher training

The performative bundling account could be used to develop pedagogical constructs and narratives that support the training of science teachers. For instance, teacher training modules in biology could introduce the idea of mental simulation of mechanisms, and the way such simulations could be seeded for complex concepts, using narratives based on everyday sensorimotor experiences. Mental simulation, and its neuroscientific basis, could thus be a central construct in training biology teachers. This approach would help ground the popular idea of teachers 'explaining' complex concepts, using contemporary empirical findings rom cognitive neuroscience. Further, the ideas related to narratives – particularly the way narratives embed and promote simulations, and the way they 'tune' initial gist simulations generated by students – could provide novice science teachers with a systematic approach to develop their classroom practices. Similarly, teacher training modules in physics could outline the way formal derivations seek to 'load' real world phenomena into equations (see Mashood et al. 2022, for details), and how this general structure could be used to develop a model-based understanding of physics. Generalising from this, the construction of all formal external models in science could thus be understood as a 'loading' process. The idea of 'loading' reality into formal terms and mathematical functions could thus be used as a systematic construct in developing science teacher training modules.

More generally, our account provides a way for teachers to approach all science topics and terms from a mechanism perspective. Apart from supporting the training of teachers in developing narratives that build mechanism models, our account also helps develop novel evaluation methods. For instance, the analysis of student understanding of the later use of defined technical terms – which requires students to re-generate the imagery (eg: leaf, pores) and simulation of a dynamic scenario (eg: opening, closing) based on the imagery – provides teachers with a systematic approach to probe a student's understanding of mechanisms. This structure, when used systematically as part of teacher training, could also help design new evaluation methods.

7.3.2 Theoretical Implications

We have extended distributed and embodied cognition theory to develop an integrated account of the way teaching, classroom, and academic language processes help develop scientific mechanism concepts in student minds. Since this account systematically extends a set of theoretical positions within cognitive science and cognitive linguistics, it has significant implications for some of the wider theories in these domains. For instance, as the PB account draws on ESTL, which is situated within the embodied cognition framework, the PB account also extends this framework. In the embodied cognition framework, which takes an integrated view of action and perception, conceptions are considered to be built up on top of the base sensorimotor layer, through the use of language and other representational forms, as well as tools, to reconfigure existing sensorimotor experiences. Approaches such as Perceptual Symbol Systems (PSS) (Barsalou, 1999) also seek to ground abstract concepts on the sensorimotor base layer. However, PSS focuses just on perception networks, and the theory does not seek to provide a process account of how another agent (like the teacher) manages to extend students' social and material experiences to load meaning into abstract concepts, by using the enactive and representational resources at their disposal. More generally, the sophistication of a teacher's explanation, and its role in the formation of student conceptions, is rarely discussed in the embodied cognition literature (Upadhyay et al., 2021; 2023).

In terms of extending related literature in cognitive linguistics, the reconfiguration role of language is examined by conceptual blending (CB) theory (Fauconnier & Turner, 1998), which analyses creative uses of language as a systematic melding of different concept frames, and the "running" of the resulting simulation. This model is very close to our proposal, and the CB theory has recently been used to analyse physics and learning experiences (Dreyfus et al., 2015; Enyedy et al., 2015; Fuchs, 2015; Gregorcic & Haglund, 2021; Hu & Rebello, 2013). However, CB theory does not consider how mental models are built up over time in student minds, through teaching narratives and intertwining with MTs, to generate componential mental structures that can be activated in specific ways, by oneself and others. Further, CB theory assumes mental simulation, while in ESTL, simulation is considered a by-product of event coding (Hommel et al., 2001) and forward models (Grush, 2004; Wolpert & Kawato, 1998), which are primarily motor control processes. This theoretical structure, which is an extension of the neo-Jamesian (ideomotor) approach to cognition, as well as motor control theory, provides ways to develop neural-level models and studies of the reconfiguration role of language (Glenberg & Gallese, 2012), particularly the way language helps reconfigure mental simulations, to develop new mechanism concepts in student minds.

The performative bundle model of mechanism terms is also somewhat similar to a model of language presented by Ramachandran and Hubbard (2001), where metaphor, and language in general, is considered a mechanism that recombines perceptual experiences, thus generating a form of "virtual" synaesthesia. This proposal is restricted to metaphors with perceptual structure, and does not include dynamics, which is central to MTs. The performative bundle model extends this language-as-recombinator view further, to reconfigurations of mental simulations, where the generated novel forms also have a performative nature. This performative structure makes the language experience closer to virtual reality experiences than synaesthesia.

These connections to existing literature indicate that the performative bundle model could be combined with these approaches, to seed new theoretical accounts and empirical approaches to study higher-order cognition. These productive possibilities illustrate how a data-driven learning sciences analysis could benefit basic cognitive science research. Specifically, our approach allows extending empirical investigations of ESTL, which currently focus on conventional meanings of verbs and other language structures. These language structures are not as dense as MTs, and they are not built up systematically using enaction. They thus do not allow studying how building is related to mental simulation. This interesting direction can be further extended, to the building and mental simulation of mathematical structures, which can also be studied from an ESTL perspective (Danesi, 2021; Lakoff & Núñez, 2000).

7.3.3 Implications for Educational Technology Design

Arthur Glenberg, one of the founders of embodied cognition and ESTL, reports an interactive system that promotes mental simulation, designed specifically to advance reading skills in primary students (Glenberg et al., 2011). The system allows students to read sentences that embed activities, while also manipulating the same activities on screen (for example, on a reading task related to Halloween, a reader reads a sentence like "Ben hooks a cart to the tractor." After reading the sentence, the reader manipulates the image of Ben with a cart, by moving it and attaching it to the tractor). This basic association framework could be extended to develop educational technologies that support students' understanding of mechanisms. A prototype system along these lines is illustrated by Salve et al. (2021).

Following our simulation-based account of AL, a key premise underlying this system is that learning and using AL is not optional while learning science, as the specific processes and states that constitute mechanisms are generated and supported by AL structures. The idea of "loading" mechanism structures and activities into specific technical terms, and using these to reactivate the mechanisms later in different contexts, has been extended in our work, to the building and use of formal structures, particularly physics equations. Interactive systems to learn derivations, based on this loading premise, have also been developed, based on 4–5 standard steps (idealisation, discretization, geometric description, algebraic description, generalisation/solving), which are key components in most physics model building (derivation) processes (Mashood et al, 2022).

These systems illustrate how the performative bundling theory could be applied to develop productive educational technological approaches that advance the teaching/learning of science. The current systems do not specifically seek to support the building of teacher narratives, but they could be easily adapted for this purpose, and also to support better teacher training.

7.3.4 Implications for Policy makers

In the Indian context, the question of AL has escaped the attention of policy makers. NEP 2020 has recognised the distinction between the first language and the school language of the learner. But this distinction does not penetrate deep enough to also consider the difference between the everyday language and the academic language (AL) that the learner has to negotiate during schooling. This is a crucial distinction which has been missed by several policy documents over the years, but is now recognised by curricular documents such as NGSS, particularly in the last few decades. In the Indian context, the recognition itself would be a step in the right direction. The AL problem is not just limited to STEM but is part of every academic discipline, and recognising this problem thus can have far reaching consequences in the design and development of an effective academic ecosystem.

7.4 Limitations and Future Work

Below we discuss some of the limitations of the three studies we carried out as part of the research reported in this thesis.

7.4.1 Study1: Biology mechanism models

a. Methodologically we wanted to make use of multiple mechanism models in each of the disciplines (both biology and physics) for development of this theoretical framework. But due to logistical constraints, especially the pandemic, this plan could not be executed.

b. Teacher interviews would have helped us to understand the teacher's perspective in developing explanations in teaching mechanism models. Due to logistical constraints, teachers could not be interviewed after their teaching sessions.

7.4.2 Study 2: Physics Derivation study

a. The interactive system improved conceptual understanding for some students, the results showed that pre-existing skills in conceptual blending played a role in students' success. More extensive classroom studies and teacher training are needed to further refine the teaching narrative and test its effectiveness in diverse educational contexts.

b. The interactive systems we have developed are proof-of-concept, and coded by student programmers. They have some glitches, and we are currently working on developing more professional versions of these systems, as well as new ones.

c. The teaching narrative we used in the study was not developed in collaboration with a range of practising teachers. In ongoing work, we are collaborating with a set of motivated teachers from the initial teaching workshops, to extend the interactive systems to 12th grade and undergraduate classrooms. We expect a more systematic teaching narrative to emerge through this project.

d. The open-ended problem used in the study was based on the teaching intuition of the researcher practitioner, as well as some discussion with practising teachers. We expect to develop a more systematic set of open-ended problems through the ongoing classroom studies.

e. The number of participants in the proof-of-concept study we report here is quite small, and they were selected based on availability. Based on the ongoing classroom-based project, we plan to report a more wide-ranging study, with a significant number of participants and more systematic sampling.

f. Only one interactive system was presented to participants, and our analysis of student performance data did not delve deep into how their problem-solving process systematically changed through the teaching narrative. In the classroom project, we will be presenting a range of derivations, including some under development. Based on this intervention, we will be examining in detail the changes in students' problem-solving processes, through their exposure to the interactive system and the new teaching narrative.

g. The results we present here are very preliminary, and only indicate proof-of-concept. Based on our experience running some further studies, the teacher workshops, and discussions with teachers and students, we expect to report more robust results soon, based on the ongoing classroom interventions.

7.4.3 Study 3: The relation between simulation and language structure

The results from the third study are tentative at the most. Robust sampling is required to improve the reliability of the results. This study can serve as a template on which a more detailed study can be designed and executed.

7.4.4 Reflecting on the enactive cognition framework from the standpoint of socio-culturally oriented frameworks

The enactive cognitive framework has the potential to provide rich mechanistic models of the interactions between teachers and students in the classroom. The micro resolution it offers makes it possible to analyse these dynamic interactions at a scale and resolution which cannot be afforded by other approaches. However, such cognitive frameworks struggle to provide a holistic account of these rich dynamic interactions operating within a larger socio-cultural context, being influenced by forces operating at a much larger scale. The following brief review summarises important works at the intersection of discourse, identity, linguistic diversity etc.

Brown's (2004) concept of **discursive identity** sheds light on how students assimilate into the culture of science by adopting its discourse. He emphasizes that English language learners often face unique challenges in reconciling their personal identities with the formal, often exclusionary, scientific discourse. Brown posits that fostering inclusive practices is critical to engaging these learners effectively. On issues pertaining to identity formation Brown (2006) delves deeper into the nuances of adopting scientific discourse, highlighting the sociolinguistic barriers students face. He argues that students must not only learn the content but also navigate a new linguistic landscape that reflects power structures within scientific communities. For instance, students perceive scientific terminology as distinctly formal and authoritative, distancing it from their everyday language. In another study focusing on Science Literacy and Cultural Relevance Brown, Reveles, and Kelly (2005) propose that scientific literacy extends beyond content knowledge to include the ability to participate in scientific discourse. This framework bridges the gap between cultural identity and academic language, underscoring the importance of culturally responsive pedagogy. This also aligns well with our view on AL in science education and contrasts with the view that mere simplification of academic jargon is useful for students.

7.4.4.1 Linguistic and Visualization Strategies in Science Teaching

Another interesting discussion pertains to what is called as `Content first Approaches' which advocates prioritizing students' comprehension of scientific concepts in their everyday language before transitioning to formal terminology (Brown and Ryoo, 2008). This scaffolding technique enables students to build foundational understanding without being hindered by complex jargon. In addition to linguistic considerations Dynamic Visualisations also plays a crucial role as far as teaching and learning of science is concerned (Ryoo and Linn, 2012 & 2014) Research has demonstrated the effectiveness of dynamic visualizations in clarifying abstract concepts, such as energy transformations in photosynthesis (Ryoo and Linn, 2012 & 2014). Their studies highlight that interactive visual tool, when paired with explanatory guidance, significantly improve conceptual understanding. Ryoo et al. (2018) explore the use of visualizations to support linguistically diverse students in understanding chemical phenomena. Their findings underscore the importance of designing accessible and inclusive instructional strategies that account for language barriers while maintaining rigour in content delivery. The interactive system for derivations and the teacher narrative that complements it is one such interactive visual tool. It makes the different modelling moves explicit, starting from reality to the abstract mathematical equation. More importantly, the interface gives students agency to interact with and manipulate the derivation. Our results demonstrate that after experiencing the system students extracted this meta narrative of the gradual transition from reality to the mathematical equation well. The inclusion of interactive visual tools as part of the classroom learning environments would enhance students' mental simulations and would align well with the enactive cognition framework.

However, model-based teaching practices would require a radical overhaul of the current pedagogical practice in a majority of the Indian classrooms which still follow traditional lecture-based methods for teaching. As inquiry-based approaches are relatively familiar to teachers they could be the next step in the transition from traditional pedagogical approaches to more student centric and scientifically authentic approaches. Windschitl (2002, 2003, 2004) identifies conceptual, pedagogical, cultural, and political challenges in implementing inquiry-based science teaching. Teachers often struggle to align theoretical ideals with classroom realities, defaulting to simplistic, atheoretical methods of inquiry. This gap highlights the need for robust teacher training and support systems. Model-based inquiry is advocated in literature as an alternative to traditional inquiry methods (Windschitl et al., 2008). This approach emphasizes constructing, testing, and revising models to reflect scientific practices. The shift from merely following procedural steps to engaging with models encourages deeper scientific reasoning and critical thinking. A core set of instructional practices designed to support science teachers in fostering inquiry and model-based learning is proposed (Windschitl et al., 2012). These practices include scaffolding student reasoning, designing investigations, and facilitating productive classroom discussions, all aligned with Next Generation Science Standards (NGSS).

Windschitl and Andre (1998) highlight the transformative potential of computer simulations in fostering conceptual change. Their research demonstrates that constructivist-designed simulations, combined with reflective activities, help students overcome misconceptions and deepen their understanding of scientific phenomena. The interplay between teacher beliefs, institutional culture, and social dynamics in integrating technology into classrooms is explored as well (Windschitl and Sahl, 2002). Their study of a laptop-integrated school reveals that successful technology adoption depends on supportive institutional structures and adaptive teaching practices. The work on technology-enhanced instruction emphasizes the importance of tailoring tools to students' linguistic and cognitive needs (Ryoo, 2015). By incorporating familiar language and interactive visualizations, technology becomes a bridge between abstract concepts and student understanding. Technology integration in the Indian education system continues to remain a challenge for several reasons related to infrastructure, teacher and student preparedness, funding etc. However, a steady improvement has been observed with increased private investment and government initiatives. True technology integration in the classroom would play an important role in enhancing both teachers and students' mental simulations by opening up more possibilities of performative affordances enriching their performative bundles. Once again, a quality teacher training program is crucial to facilitate this transition and technology adoption.

7.4.5 Future directions

The research studies carried out in this thesis can be extended across different directions. These extensions can generate connections to other similar theoretical frameworks. These could be in the form of new study designs based on the observation and analysis in the current studies. Below we explicate some possible directions in which the work reported in this thesis could be extended.

7.4.5.1 Performative Bundling as connecting Perceptual Symbol System (PSS) account to AL

Developing crosstalk between the PB theoretical construct and other related theoretical frameworks would be mutually beneficial. Below we outline the interconnectedness between PB and PSS, seeding a way towards the extension of PB.

The information processing paradigm in cognitive science undermined the capacity of the perceptual system to serve as a conceptual system, as the former was considered as just a recording system. The information processing approach postulated the transduction of amodal symbols from a perceptual experience. These amodal symbols then served as a basis for a conceptual system. This structure made the perceptual system untenable as a resource to account for cognition. The perceptual symbol systems (PSS) account (Barsalou, 1999) critiques the view of the perceptual system as a mere recording system, and argues that it also works as a conceptual system.

PSS is a perceptual theory of knowledge. It grounds the perceptual experience in its neural representation. From this structure, perceptual symbols are extracted in a top down manner. According to PSS, schematic representations of perceptual components are extracted out from perceptual experience, and stored in long term memory through selective attention, without representing it as a holistic experience. These components can be extracted for sensory-motor, proprioception, and introspective experiences. These stored memories for the same component then get organised around a common frame, and implement a simulator that produces simulations for that component. Thus, all the experiences of kicking would get organised around a common frame ‘kick’ and would be simulated when each is activated. It also has the potential to generate additional kick experiences, through introspective interaction with other perceptual symbols. PSS thus implements a conceptual system, formulated as perceptual symbols. It has sensory-motor components, along with introspection and proprioception elements, grounded in neural representations. PSS thus provides a fine-grained grounding of complex simulations in the neural representations of perceptual experiences.

In academic contexts, the problem remains that perceptual experiences are not available for the complex models being represented in the AL of a given discipline. The content being discussed in the classroom remains unconnected to the related perceptual and the introspective experiences the learner might have. Here an additional process is required to connect the learners' experiences to the content, in order to activate the stored memories of the perceptual symbols, which can get the simulations going. PB is a theoretical construct that describes this process, accounting for the teaching agent’s (the teacher in academic contexts) role in systematically binding student experiences to the mechanism terms being used to describe the mechanism model. The PSS thus gives a fine-grained account of a perceptual system that is conceptual, which can form the basis of ESTL. PB builds on ESTL, describing the systematic bundling of these perceptual and higher order experiences, such as introspective experiences and their organisation, around the common frame of the mechanism terms (MT’s), which can then run the related simulation when activated.

7.4.5.2 Towards an Enactive Account of Academic Language and Its Learning

The PB account provides a starting point to understand the nature of teacher narratives, and how they help build new mental models of mechanisms. However, the teacher narratives are highly modulated by the way textbooks encode mechanisms, as the teachers seek to accurately enact—and thus replicate in student minds—the textbook descriptions of mechanisms. This narrative-modulating role of the encoding text suggests that a theoretical account of the way textbooks encode mechanisms needs to be developed, to understand the constraints guiding teacher narratives of mechanisms. This account is particularly needed to develop teacher training modules based on the performative bundle approach.

The textbook encoding of mechanisms is based on academic language (AL), which crucially mediates the teaching of science (Halliday & Martin, 2003). Further, the structure of AL is considered to promote the transition to scientific thinking. Academic language is very wide, complex, and not clearly characterised. Developing a full theoretical account of the way AL encodes mechanisms is thus a long-term project and beyond the scope of this thesis. However, the account we have developed presents a starting point to develop such a wider theoretical model, by outlining a preliminary enactive account of one aspect of AL (nominalization), and the role it plays in encoding—and generating—mechanism models.

The structure of academic language is very different from the language students use in day-to-day life, as AL has features that are different from everyday language (EL). Most students find the transition from EL to AL challenging (Lemke, 1990), possibly because AL features embed a new worldview, and processing AL requires related perspective shifts and concept formation. The transition to AL is particularly difficult for students in non- English-speaking countries (with English-based science curricula), as learning of science concepts in such contexts requires learning both English and AL simultaneously (Setati et al., 2002). Many students in such countries are first-generation learners, with no support from their families and communities for learning. This makes the transition to AL extremely difficult. Supporting this view, recent neuroimaging work shows that parents' language skills correlate with students' reading abilities and related functional connectivity (Su et al., 2022).

Given the critical role of AL in science learning, a central focus of science education research is the design of new ways to help students gain fluency in AL. Most studies in this area are descriptive, and follow three broad strands: characterising the nature of AL (Schleppegrell, 2001), understanding the nature of students' difficulties while shifting from EL to AL (Snow & Uccelli, 2009), and the design of learning interventions that seek to scaffold the shift to AL (Cummins, 2000; Glenberg et al., 2011). Complementing these approaches, the performative bundle model can lead to a different and more general account of AL. Such an account can help develop an understanding of the cognitive mechanisms involved in the way AL mediates science learning and conceptual transitions, and thus lead to novel pedagogy designs that build on this understanding.

References

Abrahamson, D., & Sánchez-García, R. (2016). Learning Is Moving in New Ways: The Ecological Dynamics of Mathematics Education. *Journal of the Learning Sciences*, *25*(2), 203–239. https://doi.org/10.1080/10508406.2016.1143370

Alger, C. (2009). Secondary teachers' conceptual metaphors of teaching and learning: Changes over the career span. *ScienceDirect*, *25*, 743–751.

Alibali, M. W., Spencer, R. C., Knox, L., & Kita, S. (2011). Spontaneous gestures influence strategy choices in problem solving. *Psychological Science*, *22*(9), 1138–1144.

Amin, T. G. (2009). Conceptual Metaphor Meets Conceptual Change. *Human Development*, *52*(3), 165–197. https://doi.org/10.1159/000213891

Amin, T. G. (2017). Conceptual Metaphor and the Study of Conceptual Change: Research synthesis and future directions. In *Conceptual metaphor and embodied cognition in science learning*. Routledge.

Amin, T. G., Jeppsson, F., & Haglund, J. (2015). Conceptual Metaphor and Embodied Cognition in Science Learning: Introduction to special issue. *International Journal of Science Education*, *37*(5–6), 745–758. https://doi.org/10.1080/09500693.2015.1025245

Annamalai, E. (2004). Medium of power: The question of English in education in India. *Medium of Instruction Policies: Which Agenda? Whose Agenda*, 177–194.

Anstrom, K., DiCerbo, P., Butler, F., Katz, A., Millet, J., & Rivera, C. (2010). *A Review of the Literature on Academic English: Implications for K-12 English Language Learners*.

Aurigemma, J., Chandrasekharan, S., Nersessian, N. J., & Newstetter, W. (2013). Turning experiments into objects: The cognitive processes involved in the design of a lab-on-a-chip device. *Journal of Engineering Education*, *102*(1), 117–140.

Bak, T. H., & Chandran, S. (2012). What wires together dies together: Verbs, actions and neurodegeneration in motor neuron disease. *Cortex*, *48*(7), 936–944.

Bansal, G. (2022). The hegemony of English in science education in India: A case study exploring impact of teacher orientation in translating policy in practice. *Cultural Studies of Science Education*, *17*(2), 439–466.

Barker, M., & Carr, M. (1989). Teaching and learning about photosynthesis. Part 1: An assessment in terms of students' prior knowledge. *International Journal of Science Education*, *11*(1), 49–56.

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, *22*(4), 577–660.

Barsalou, L. W. (2008). Grounded cognition. *Annu. Rev. Psychol.*, *59*(1), 617–645.

Beer, R. D. (1995). A dynamical systems perspective on agent-environment interaction. *Artificial Intelligence*, *72*(1–2), 173–215.

Bergen, B. (2015). Embodiment, simulation and meaning. In *The Routledge handbook of semantics* (pp. 142–157). Routledge.

Bergen, B. K., Lindsay, S., Matlock, T., & Narayanan, S. (2007). Spatial and linguistic aspects of visual imagery in sentence comprehension. *Cognitive Science*, *31*(5), 733–764.

Bergen, B., & Wheeler, K. (2010). Grammatical aspect and mental simulation. *Brain and Language*, *112*(3), 150–158.

Bernstein, B. (2003). *Class, codes and control: Applied studies towards a sociology of language* (Vol. 2). Psychology Press.

Biskjaer, M. M., Fischel, A., Dove, G., & Halskov, K. (2018). How Materials Support Conceptual Blending in Ideation. *In Storni, C., Leahy, K., McMahon, M., Lloyd, P. and Bohemia, E. (Eds.), Design as a Catalyst for Change*. DRS International Conference, Limerick, Ireland. https://dl.designresearchsociety.org/drs-conference-papers/drs2018/researchpapers/66

Bokulich, A. (2017). Models and explanation. *Springer Handbook of Model-Based Science*, 103–118.

Bourdieu, P. (1984). A social critique of the judgement of taste. *Traducido Del Francés Por R. Nice. Londres, Routledge*. http://www.alejandra-aeron.com/pdf/bordieu.pdf

Brizuela, B. M., & Gravel, B. E. (Eds.). (2013). *"Show me what you know": Exploring student representations across STEM disciplines*. Teachers College Press, Teachers College, Columbia University.

Brown, B. (2004). Discursive identity: Assimilation into the culture of science and its implications for minority students. *Journal of Research in Science Teaching*, *41*(8), 810–834.

Brown, B. (2006). "It isn't no slang that can be said about this stuff": Language, identity, and appropriating science discourse. *Journal of Research in Science Teaching*, *43*(1), 96–126. https://doi.org/10.1002/tea.20096

Brown, B. A., Reveles, J. M., & Kelly, G. J. (2005). Scientific literacy and discursive identity: A theoretical framework for understanding science learning. *Science Education*, *89*(5), 779–802. https://doi.org/10.1002/sce.20069

Brown, B. A., & Ryoo, K. (2008). Teaching science as a language: A "content-first" approach to science teaching. *Journal of Research in Science Teaching*, *45*(5), 529–553. https://doi.org/10.1002/tea.20255

Bub, D. N., & Masson, M. E. (2012). On the dynamics of action representations evoked by names of manipulable objects. *Journal of Experimental Psychology: General*, *141*(3), 502.

Canal, P. (1999). Photosynthesis and "inverse respiration" in plants: An inevitable misconception? *International Journal of Science Education*, *21*(4), 363–371. https://doi.org/10.1080/095006999290598

Carey, S. (2000). The Origin of Concepts. *Journal of Cognition and Development*, *1*(1), 37–41. https://doi.org/10.1207/S15327647JCD0101N_3

Cartwright, N. (1997). Where do laws of nature come from? *Dialectica*, *51*(1), 65–78.

Chamot, A. U., & O'Malley, J. M. (1996). The Cognitive Academic Language Learning Approach: A Model for Linguistically Diverse Classrooms. *The Elementary School Journal*, *96*(3), 259–273. https://doi.org/10.1086/461827

Chandrasekharan, S. (2009). Building to discover: A common coding model. *Cognitive Science*, *33*(6), 1059–1086.

Chandrasekharan, S. (2014). Becoming knowledge: Cognitive and neural mechanisms that support scientific intuition. *Rational Intuition: Philosophical Roots, Scientific Investigations*, 307–337.

Chandrasekharan, S., & Nersessian, N. J. (2015). Building cognition: The construction of computational representations for scientific discovery. *Cognitive Science*, *39*(8), 1727–1763.

Chandrasekharan, S., & Nersessian, N. J. (2021). Rethinking correspondence: How the process of constructing models leads to discoveries and transfer in the bioengineering sciences. *Synthese*, *198*, 1–30.

Chandrasekharan, S., Nersessian, N. J., & Subramanian, V. (2012). Computational modeling: Is this the end of thought experiments in science? In *Thought experiments in science, philosophy, and the arts* (pp.

239–260). Routledge.

Charalambous, C. Y., Hill, H. C., & Ball, D. L. (2011). Prospective teachers' learning to provide instructional explanations: How does it look and what might it take? *Journal of Mathematics Teacher Education*, *14*(6), 441–463. https://doi.org/10.1007/s10857-011-9182-z

Chemero, A. (2013). Radical embodied cognitive science. *Review of General Psychology*, *17*(2), 145–150.

Chi, M. T. H. (2005). Commonsense Conceptions of Emergent Processes: Why Some Misconceptions Are Robust. *Journal of the Learning Sciences*, *14*(2), 161–199. https://doi.org/10.1207/s15327809jls1402_1

Clark, A. (1997). The dynamical challenge. *Cognitive Science*, *21*(4), 461–481.

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences*, *36*(3), 181–204.

Clark, A., & Toribio, J. (1994). Doing without representing? *Synthese*, *101*, 401–431.

Clark, D. B. (2006). Longitudinal Conceptual Change in Students' Understanding of Thermal Equilibrium: An Examination of the Process of Conceptual Restructuring. *Cognition and Instruction*, *24*(4), 467–563. https://doi.org/10.1207/s1532690xci2404_3

Clement, J. (1994). Use of physical intuition and imagistic simulation in expert problem solving. *Implicit and Explicit Knowledge: An Educational Approach.*, 204–244.

Clement, J. J. (2003). *Imagistic simulation in scientific model construction*. *25*(25).

Clement, J., Zietsman, A., & Monaghan, J. (2005). Imagery in science learning in students and experts. *Visualization in Science Education*, 169–184.

Coffin, C., & Donohue, J. P. (2012). Academic Literacies and systemic functional linguistics: How do they relate? *Journal of English for Academic Purposes*, *11*(1), 64–75. https://doi.org/10.1016/j.jeap.2011.11.004

Connor, C. M., Radach, R., Vorstius, C., Day, S. L., McLean, L., & Morrison, F. J. (2015). Individual Differences in Fifth Graders' Literacy and Academic Language Predict Comprehension Monitoring Development: An Eye-Movement Study. *Scientific Studies of Reading*. https://www.tandfonline.com/doi/full/10.1080/10888438.2014.943905

Conrad, D., & Libarkin, J. C. (2022). Using Conceptual Metaphor Theory within the Model of Educational Reconstruction to identify students' alternative conceptions and improve instruction: A plate tectonics example. *Journal of Geoscience Education*, *70*(2), 262–277. https://doi.org/10.1080/10899995.2021.1983941

Corni, F., Fuchs, H. U., & Dumont, E. (2019). Conceptual metaphor in physics education: Roots of analogy, visual metaphors, and a primary physics course for student teachers. *Journal of Physics: Conference Series*, *1286*(1), 012059. https://doi.org/10.1088/1742-6596/1286/1/012059

Coulson, S. (2001). *Semantic Leaps: Frame-Shifting and Conceptual Blending in Meaning Construction*. Cambridge University Press.

Coulson, S. (2008). Conceptual blending in thought, rhetoric, and ideology. In *Cognitive Linguistics* (pp. 187–210). De Gruyter Mouton. https://www.degruyter.com/document/doi/10.1515/9783110197761.2.187/pdf?licenseType=restricted

Craver, C., Tabery, J., & Illari, P. (2019). *Mechanisms in science*.

Cummins, J. (2000). 4 Putting Language Proficiency in its Place: Responding to critiques of the conversational/academic language distinction. In *English in Europe* (pp. 54–83). Multilingual Matters.

https://doi.org/10.21832/9781800417991-005

Cutting, J. E. (1982). Two ecological perspectives: Gibson vs. Shaw and Turvey. *The American Journal of Psychology*, 199–222.

Daane, A. R., Haglund, J., Robertson, A. D., Close, H. G., & Scherr, R. E. (2018). The pedagogical value of conceptual metaphor for secondary science teachers. *Science Education*, *102*(5), 1051–1076. https://doi.org/10.1002/sce.21451

Dagher, Z., & Cossman, G. (1992). Verbal explanations given by science teachers: Their nature and implications. *Journal of Research in Science Teaching*, *29*(4), 361–374. https://doi.org/10.1002/tea.3660290405

Danesi, M. (2003). *Conceptual metaphor theory and the teaching of mathematics: Findings of a pilot project*. *2003*(145), 71–83. https://doi.org/10.1515/semi.2003.061

Danesi, M. (2007). A conceptual metaphor framework for the teaching of mathematics. *Studies in Philosophy and Education*, *26*(3), 225–236. https://doi.org/10.1007/s11217-007-9035-5

Danesi, M. (2021). Blending Theory and Mathematical Cognition. In M. Danesi (Ed.), *Handbook of Cognitive Mathematics* (pp. 1–22). Springer International Publishing. https://doi.org/10.1007/978-3-030-44982-7_50-1

Daniello, F., Turgut, G., & Brisk, M. (2014). Applying Systemic Functional Linguistics to Build Educators' Knowledge of Academic English for the Teaching of Writing | SpringerLink. In *Englishes in Multilingual contexts* (Vol. 10). https://link.springer.com/chapter/10.1007/978-94-017-8869-4_11

Di Paolo, E., Bhurman, T., & Barandiaran, X. (2017). *Sensorimotor Life: An enactive proposal*. Oxford University Press.

DiCerbo, P. A., Anstrom, K. A., Baker, L. L., & Rivera, C. (2014). A Review of the Literature on Teaching Academic English to English Language Learners. *Review of Educational Research*, *84*(3), 446–482. https://doi.org/10.3102/0034654314532695

Dickmeyer, N. (1989). Metaphor, Model, and Theory in Education Research. *Teachers College Record*, *91*(2), 151–160. https://doi.org/10.1177/016146818909100204

diSessa, A. A., Gillespie, N. M., & Esterly, J. B. (2004). Coherence versus fragmentation in the development of the concept of force. *Cognitive Science*, *28*(6), 843–900. https://doi.org/10.1207/s15516709cog2806_1

Dreyfus, B., Gupta, A., & Redish, E. (2018). Applying Conceptual Blending to Model Coordinated Use of Multiple Ontological Metaphors. In *Conceptual metaphor and embodied cognition in science learning* (pp. 80–106). Routledge. https://doi.org/10.4324/9781315316925-8

Dreyfus, T. (2015). *Constructing abstract mathematical knowledge in context*. 115–133.

Duff, P. A. (2010). Language Socialization into Academic Discourse Communities. *Annual Review of Applied Linguistics*, *30*, 169–192. https://doi.org/10.1017/S0267190510000048

Eggins, S. (2004). *Introduction to Systemic Functional Linguistics: 2nd Edition*. A&C Black.

Enyedy, N., Danish, J. A., & DeLiema, D. (2015). Constructing liminal blends in a collaborative augmented-reality learning environment. *International Journal of Computer-Supported Collaborative Learning*, *10*, 7–34.

Eynde, S. V. den, Schermerhorn, B. P., Deprez, J., Goedhart, M., Thompson, J. R., & Cock, M. D. (2020). Dynamic conceptual blending analysis to model student reasoning processes while integrating mathematics and physics: A case study in the context of the heat equation. *Physical Review Physics Education Research*, *16*(1), 010114. https://doi.org/10.1103/PhysRevPhysEducRes.16.010114

Fauconnier, G. (2001). Conceptual Blending and Analogy. In D. Gentner, K. J. Holyoak, & B. N. Kokinov (Eds.), *The Analogical Mind: Perspectives from Cognitive Science* (p. 0). The MIT Press. https://doi.org/10.7551/mitpress/1251.003.0011

Fauconnier, G., & Turner, M. (1998). Conceptual integration networks. *Cognitive Science*, *22*(2), 133–187.

Fauconnier, G., & Turner, M. (2011). Polysemy and conceptual blending. In B. Nerlich, Z. Todd, V. Herman, & D. D. Clarke (Eds.), *Polysemy: Flexible Patterns of Meaning in Mind and Language* (pp. 79–94). De Gruyter Mouton. https://doi.org/10.1515/9783110895698.79

Figueroa, J., Meneses, A., & Chandia, E. (2018). Academic language and the quality of written arguments and explanations of Chilean 8th graders. *Reading and Writing*, *31*(3), 703–723. https://doi.org/10.1007/s11145-017-9806-5

Fitzgerald, J., Elmore, J., Relyea, J. E., & Stenner, A. J. (2020). Domain-specific academic vocabulary network development in elementary grades core disciplinary textbooks. *Journal of Educational Psychology*, *112*(5), 855–879. https://doi.org/10.1037/edu0000386

Fitzgerald, J., Relyea, J. E., & Elmore, J. (2022). Academic vocabulary volume in elementary grades disciplinary textbooks. *Journal of Educational Psychology*, *114*(6), 1257–1276. https://doi.org/10.1037/edu0000735

Fodor, J. A. (1975). *The Language of Thought* (Vol. 87, Issue 1). Harvard University Press.

Fredriksson, A., & Pelger, S. (2020). Conceptual Blending Monitoring Students' Use of Metaphorical Concepts to Further the Learning of Science. *Research in Science Education*, *50*(3), 917–940. https://doi.org/10.1007/s11165-018-9717-8

French, A. (2003). *Vibrations and Waves: The MIT Introductory Physics Series*.

Fuchs, L. S., Fuchs, D., Compton, D. L., Hamlett, C. L., & Wang, A. Y. (2015). Is word-problem solving a form of text comprehension? *Scientific Studies of Reading*, *19*(3), 204–223.

Fuson, K., & Briars, D. (2024). *Using a Base-Ten Blocks Learning/Teaching Approach for First- and Second-Grade Place-Value and Multidigit Addition and Subtraction*. *21*(3), 180–206.

Fyfe, E. R., & Nathan, M. J. (2019). Making "concreteness fading" more concrete as a theory of instruction for promoting transfer. *Educational Review*, *71*(4), 403–422.

Galloway, E. P., & Uccelli, P. (2015). Modeling the relationship between lexico-grammatical and discourse organization skills in middle grade writers: Insights into later productive language skills that support academic writing. *Reading and Writing*, *28*(6), 797–828. https://doi.org/10.1007/s11145-015-9550-7

Gebhard, M. (2010). Teacher Education in Changing Times: A Systemic Functional Linguistics (SFL) Perspective. *TESOL Quarterly*, *44*(4), 797–803.

Geelan, D. (2013). Teacher Explanation of Physics Concepts: A Video Study. *Research in Science Education*, *43*(5), 1751–1762. https://doi.org/10.1007/s11165-012-9336-8

Geeraerts, D. (Ed.). (2006). *Cognitive linguistics: Basic readings*. Mouton de Gruyter.

Gibbs Jr., R. W. (2011). Evaluating Conceptual Metaphor Theory. *Discourse Processes*, *48*(8), 529–562. https://doi.org/10.1080/0163853X.2011.606103

Gibbs Jr., R. W. (2014). Conceptual metaphor in thought and social action. In *The power of metaphor: Examining its influence on social life* (pp. 17–40). American Psychological Association. https://doi.org/10.1037/14278-002

Gibbs, R. W. (2009). Why Do Some People Dislike Conceptual Metaphor Theory? *Cognitive Semiotics*, *5*(1–2), 14–36. https://doi.org/10.1515/cogsem.2013.5.12.14

Gibson, J. J. (2014). *The Ecological Approach to Visual Perception: Classic Edition* (1st ed.). Psychology Press. https://doi.org/10.4324/9781315740218

Glaser, B. G., & Strauss, A. L. (2017). *The Discovery of Grounded Theory: Strategies for Qualitative Research* (1st ed.). Routledge. https://doi.org/10.4324/9780203793206

Glenberg, A. M. (2011). How reading comprehension is embodied and why that matters. *International Electronic Journal of Elementary Education*, *4*(1), 5–18.

Glenberg, A. M., & Gallese, V. (2012). Action-based language: A theory of language acquisition, comprehension, and production. *Cortex*, *48*(7), 905–922.

Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin & Review*, *9*(3), 558–565. https://doi.org/10.3758/BF03196313

Glenberg, A. M., Witt, J. K., & Metcalfe, J. (2013). From the revolution to embodiment: 25 years of cognitive psychology. *Perspectives on Psychological Science*, *8*(5), 573–585.

Glennan, S. (2017). *The new mechanical philosophy*. Oxford University Press.

Goldin-Meadow, S., & Singer, M. A. (2003). From children's hands to adults' ears: Gesture's role in the learning process. *Developmental Psychology*, *39*(3), 509.

Gottlieb, M., & Ernst-Slavit, G. (2014). *Academic Language in Diverse Classrooms: Definitions and Contexts*. Corwin Press.

Gray, M. E., & Holyoak, K. J. (2021). Teaching by analogy: From theory to practice. *Mind, Brain, and Education*, *15*(3), 250-263.

Gregorcic, B., & Haglund, J. (2021). Conceptual Blending as an Interpretive Lens for Student Engagement with Technology: Exploring Celestial Motion on an Interactive Whiteboard. *Research in Science Education*, *51*(2), 235–275. https://doi.org/10.1007/s11165-018-9794-8

Grush, R. (2004). The emulation theory of representation: Motor control, imagery, and perception. *Behavioral and Brain Sciences*, *27*(3), 377–396.

Gupta, D. (2013). Teaching English to engineering students in India. *Journal of Education and Practice*, *4*(11), 131–137.

Halliday, D., Resnick, R., & Walker, J. (2013). *Fundamentals of physics*. John Wiley & Sons.

Halliday, M. A. K., & Martin, J. R. (2003). *Writing science: Literacy and discursive power*. Taylor & Francis. https://books.google.com/books?hl=en&lr=&id=ZDB6AgAAQBAJ&oi=fnd&pg=PP1&dq=Halliday,+M.+A.+K.,+%26+Martin,+J.+R.+(2003).+Writing+science:+Literacy+and+discursive+power.+Taylor+%26+Francis.&ots=iUlzfrl9as&sig=rBCnxj2C_nLyTH12_g0RPxJRnhs

Hamel, J., Dufour, S., & Fortin, D. (1993). *Case study methods* (Vol. 32). Sage publications.

Harper, C., Tran, K., & Cooper, S. (2024). Conceptual Metaphor Theory in Action: Insights into Student Understanding of Computing Concepts. *Proceedings of the 55th ACM Technical Symposium on Computer Science Education V. 1*, 463–469. https://doi.org/10.1145/3626252.3630812

Havas, D. A., Glenberg, A. M., Gutowski, K. A., Lucarelli, M. J., & Davidson, R. J. (2010). Cosmetic use of botulinum toxin-A affects processing of emotional language. *Psychological Science*, *21*(7), 895-900.

Heath, S. B. (1983). *Ways with words: Language, life and work in communities and classrooms*. cambridge university Press. https://books.google.com/books?hl=en&lr=&id=ZvwEDOhLbpEC&oi=fnd&pg=PR14&dq=Heath,+1

983&ots=mpASNBBZqM&sig=VQLVTAfSjr3xQwvBf-ZV3mw0Fa4

Hegarty, M. (2004). Dynamic visualizations and learning: Getting to the difficult questions. *Learning and Instruction*, *14*(3), 343–351.

Hestenes, D. (2006). *Notes for a modeling theory*. *31*, 27.

Hoehn, J. R., Finkelstein, N. D., & Gupta, A. (2016). Conceptual blending as a tool for analyzing group discourse. *2016 Physics Education Research Conference Proceedings*, 152–155. https://doi.org/10.1119/perc.2016.pr.033

Hofer, B. K. (2000). Dimensionality and disciplinary differences in personal epistemology. *Contemporary Educational Psychology*, *25*(4), 378–405.

Hoffenberg, R., & Saxton, E. (2015). Scientific Explanations: A Comparative Case Study of Teacher Practice and Student Performance. *Electronic Journal of Science Education*, *19*(5), n5.

Hollan, J., Hutchins, E., & Kirsh, D. (2000). Distributed cognition: Toward a new foundation for human-computer interaction research. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *7*(2), 174–196.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, *24*(5), 849–878.

Hrepic, Z., Zollman, D. A., & Rebello, N. S. (2010). Identifying students' mental models of sound propagation: The role of conceptual blending in understanding conceptual change. *Physical Review Special Topics—Physics Education Research*, *6*(2), 020114.

Hu, D., & Rebello, N. S. (2013). Using conceptual blending to describe how students use mathematical integrals in physics. *Physical Review Special Topics—Physics Education Research*, *9*(2), 020118.

Hutchins, E. (1995). How a cockpit remembers its speeds. *Cognitive Science*, *19*(3), 265–288.

Hutchins, E. (2000). Distributed cognition. *International Encyclopedia of the Social and Behavioral Sciences. Elsevier Science*, *138*, 1–10.

Hutchins, E. (2005). Material anchors for conceptual blends. *Journal of Pragmatics*, *37*(10), 1555–1577. https://doi.org/10.1016/j.pragma.2004.06.008

Hutchins, E. (2006). *Cognition in the wild* (8. pr). MIT Press.

Illari, P. M., & Williamson, J. (2012). What is a mechanism? Thinking about mechanisms across the sciences. *European Journal for Philosophy of Science*, *2*, 119–135.

Ioannides, C., & Vosniadou, S. (2002). The changing meanings of force. *Cognitive Science Quarterly*, *2*(1), 5–62.

Kahneman, D., & Miller, D. T. (1986). Norm theory: Comparing reality to its alternatives. *Psychological Review*, *93*(2), 136.

Kallery, M., & Psillos, D. (2004). Anthropomorphism and animism in early years science: Why teachers use them, how they conceptualise them and what are their views on their use. *Research in Science Education*, *34*, 291–311.

Kalra, M. B., & Baveja, B. (2012). Teacher Thinking about Knowledge, Learning and Learners: A Metaphor Analysis. *3rd. International Conference on New Horizons in Education - INTE 2012*, *55*, 317–326. https://doi.org/10.1016/j.sbspro.2012.09.509

Kirsh, D. (2010). Thinking with external representations. *AI & Society*, *25*, 441–454.

Kleppner, D. (2014). *An Introduction To Mechanics*. Cambridge University Press.

Knuuttila, T., & Boon, M. (2011). How do models give us knowledge? The case of Carnot's ideal heat engine. *European Journal for Philosophy of Science*, *1*, 309–334.

Koedinger, K. R., Alibali, M. W., & Nathan, M. J. (2008). Trade-offs between grounded and abstract representations: Evidence from algebra problem solving. *Cognitive Science*, *32*(2), 366–397.

Kövecses, Z. (2008). Conceptual metaphor theory: Some criticisms and alternative proposals. *Annual Review of Cognitive Linguistics*, *6*(1), 168–184. https://doi.org/10.1075/arcl.6.08kov

Krall, R. M., Lott, K. H., & Wymer, C. L. (2009). Inservice Elementary and Middle School Teachers' Conceptions of Photosynthesis and Respiration. *Journal of Science Teacher Education*, *20*(1), 41–55. https://doi.org/10.1007/s10972-008-9117-4

Kumari, S. (2016). Learning science with analogies and metaphors. *Learning Community-An International Journal of Educational and Social Development*, *7*(2), 199–202.

Kuo, E., Hull, M. M., Gupta, A., & Elby, A. (2013). How students blend conceptual and formal mathematical reasoning in solving physics problems. *Science Education*, *97*(1), 32–57.

Lachner, A., & Nückles, M. (2016). Tell me why! Content knowledge predicts process-orientation of math researchers' and math teachers' explanations. *Instructional Science*, *44*(3), 221–242. https://doi.org/10.1007/s11251-015-9365-6

Làdavas, E. (2002). Functional and dynamic properties of visual peripersonal space. *Trends in Cognitive Sciences*, *6*(1), 17–22.

Lakoff, G., & Núñez, R. E. (2000). Where mathematics comes from: How the embodied mind brings mathematics into being. *Where Mathematics Comes from: How the Embodied Mind Brings Mathematics into Being.*, xvii, 493–xvii, 493.

Landriscina, F. (2015). The role of mental simulation in understanding and in creating scientific concepts. *Innovazione Nella Didattica Delle Scienze Nella Scuola Primaria e Dell'infanzia: Al Crocevia Fra Discipline Scientifiche e Umanistiche*, *141*.

Leite, L., Mendoza, J., & Borsese, A. (2007). Teachers' and prospective teachers' explanations of liquid-state phenomena: A comparative study involving three European countries. *Journal of Research in Science Teaching*, *44*(2), 349–374. https://doi.org/10.1002/tea.20122

Ligorio, M. B., Loperfido, F. F., Sansone, N., & Spadaro, P. F. (2011). Blending Educational Models to Design Blended Activities. In *Techniques for Fostering Collaboration in Online Learning Communities: Theoretical and Practical Perspectives* (pp. 64–81). IGI Global. https://doi.org/10.4018/978-1-61692-898-8.ch005

Liu, N., & Bergen, B. (2016). When do language comprehenders mentally simulate locations? *Cognitive Linguistics*, *27*(2), 181–203.

Lucero, A. (2012). Demands and opportunities: Analyzing academic language in a first grade dual language program. *Linguistics and Education*, *23*(3), 277–288. https://doi.org/10.1016/j.linged.2012.05.004

Lucero, A. (2014). Teachers' use of linguistic scaffolding to support the academic language development of first-grade emergent bilingual students. *Journal of Early Childhood Literacy*, *14*(4), 534–561. https://doi.org/10.1177/1468798413512848

Machamer, P., Darden, L., & Craver, C. F. (2000). Thinking about mechanisms. *Philosophy of Science*, *67*(1), 1–25.

Majumdar, R., Kothiyal, A., Ranka, A., Pande, P., Murthy, S., Agarwal, H., & Chandrasekharan, S. (2014). The Enactive equation: Exploring How Multiple External Representations are Integrated, Using a Fully Controllable Interface and Eye-Tracking. *2014 IEEE Sixth International Conference on Technology for Education*, 233–240. https://doi.org/10.1109/T4E.2014.31

Mak, M., & Willems, R. M. (2019). Mental simulation during literary reading: Individual differences revealed with eye-tracking. *Language, Cognition and Neuroscience*, *34*(4), 511–535.

Maravita, A., & Iriki, A. (2004). Tools for the body (schema). *Trends in Cognitive Sciences*, *8*(2), 79–86.

Markauskaite, L., & Goodyear, P. (2017). Learning as construction of actionable concepts: A multimodal blending perspective. *"Education in the Crossroads of Economy and Politics Role of Research in the Advancement of Public Good."* the 17th Biennial EARLI Conference for Research on Learning and Instruction "Education in the Crossroads of Economy and Politics Role of Resear ch in the Advancement of Public Good"., Tampere, Finland.

Marmaroti, P., & Galanopoulou, D. (2006). Pupils' Understanding of Photosynthesis: A questionnaire for the simultaneous assessment of all aspects. *International Journal of Science Education*, *28*(4), 383–403. https://doi.org/10.1080/09500690500277805

Martin, J. R. (2014). Evolving systemic functional linguistics: Beyond the clause. *Functional Linguistics*, *1*(1), 3. https://doi.org/10.1186/2196-419X-1-3

Martin, J. R. (2016). Meaning matters: A short history of systemic functional linguistics. *WORD*, *62*(1), 35–58. https://doi.org/10.1080/00437956.2016.1141939

Martin, T., & Schwartz, D. L. (2005). Physically distributed learning: Adapting and reinterpreting physical environments in the development of fraction concepts. *Cognitive Science*, *29*(4), 587–625.

Mashood, K., Khosla, K., Prasad, A., V, S., CH, M. A., Jose, C., & Chandrasekharan, S. (2022). Participatory approach to introduce computational modeling at the undergraduate level, extending existing curricula and practices: Augmenting derivations. *Physical Review Physics Education Research*, *18*(2), 020136.

Matlock, T. (2004). Fictive motion as cognitive simulation. *Memory & Cognition*, *32*(8), 1389–1400. https://doi.org/10.3758/BF03206329

Matthiessen, C. (2019). Register in Systemic Functional Linguistics. *Register Studies*, *1*, 10–41. https://doi.org/10.1075/rs.18010.mat

McClelland, J. L., & Elman, J. L. (1986). The TRACE model of speech perception. *Cognitive psychology*, *18*(1), 1-86.

McGlone, M. S. (2007). What is the explanatory value of a conceptual metaphor? *Language & Communication*, *27*(2), 109–126. https://doi.org/10.1016/j.langcom.2006.02.016

McNeill, K. L., & Krajcik, J. (2008). Scientific explanations: Characterizing and evaluating the effects of teachers' instructional practices on student learning. *Journal of Research in Science Teaching*, *45*(1), 53–78. https://doi.org/10.1002/tea.20201

McNeill, K. L., Lizotte, D. J., Krajcik, J., & Marx, R. W. (2004). *Supporting students' construction of scientific explanations using scaffolded curriculum materials and assessments*. Annual Conference of the American Educational Research Association, San Diego.

Merriam, S. B. (1998). *Qualitative Research and Case Study Applications in Education. Revised and Expanded from" Case Study Research in Education.".* ERIC.

Métioui, A., Matoussi, F., & Trudel, L. (2016). The Teaching of Photosynthesis in Secondary School: A History of the Science Approach. *Journal of Biological Education*, *50*(3), 275–289. https://doi.org/10.1080/00219266.2015.1085427

Miller, G. A. (2003). The cognitive revolution: a historical perspective. *Trends in cognitive sciences*, *7*(3), 141-144.

Miranda, M., Gonzalez Campo, C., Birba, A., Neely, A., Toro-Hernández, F. D., Faure, E., Rojas, G. M., Ibáñez, A., & García, A. (2022). An action-concept processing advantage in a patient with a double motor cortex. *Brain and Cognition*, *156*, 105831. https://doi.org/10.1016/j.bandc.2021.105831

Mohanty, A. K. (2006). Multilingualism of the unequals and predicaments of education in India: Mother tongue or other tongue. *Imagining Multilingual Schools*, *262*, 283.

Nagy, W., & Townsend, D. (2012). *Words as Tools: Learning Academic Vocabulary as Language Acquisition*. *47*(1), 91–108. https://doi.org/10.1002/RRQ.011

Nathan, M. J. (2012). Rethinking formalisms in formal education. *Educational Psychologist*, *47*(2), 125–148.

Nersessian, N. (1992). How do scientists think? Capturing the dynamics of conceptual change in science. *Minnesota Studies in the Philosophy of Science*, *15*.

Nersessian, N. J. (2010). *Creating scientific concepts*. MIT press.

Neumann, R. (2009). Disciplinarity. In *The Routledge international handbook of higher education* (pp. 487–500). Routledge.

Nicholson, D. J. (2012). The concept of mechanism in biology. *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences*, *43*(1), 152–163.

Niebert, K., & Gropengiesser, H. (2017). Understanding Starts in the Mesocosm: Conceptual metaphor as a framework for external representations in science teaching. In *Conceptual metaphor and embodied cognition in science learning*. Routledge.

Norman, D. A. (1993). Cognition in the head and in the world: An introduction to the special issue on situated action. *Cognitive Science*, *17*(1), 1–6.

Oakley, T. V. (1998). *Conceptual blending, narrative discourse, and rhetoric*. *9*(4), 321–360. https://doi.org/10.1515/cogl.1998.9.4.321

Odden, T. O. B. (2021). How conceptual blends support sensemaking: A case study from introductory physics. *Science Education*, *105*(5), 989–1012.

O'Hallaron, C., Palinscar, A., & Schleppegrell, M. (2015). *Reading science: Using systemic functional linguistics to support critical language awareness*. *32*, 55–67.

Pande, P., & Chandrasekharan, S. (2017). Representational competence: Towards a distributed and embodied cognition account. *Studies in Science Education*, *53*(1), 1–43.

Pande, P., & Chandrasekharan, S. (2022). Expertise as sensorimotor tuning: Perceptual navigation patterns mark representational competence in science. *Research in Science Education*, *52*(2), 725–747.

Pandey, K. K., & Jha, S. (2023). Exploring the interrelationship between culture and learning: The case of English as a second language in India. *Asian Englishes*, *25*(3), 343–359.

Patra, B., & Mohanty, A. K. (2016). Importance of english for engineering students: An evaluation of the prevalent teaching-learning system in the indian context. *International Journal of English and Literature (IJEL), ISSN (P)*, 2249–6912.

Pérez, R. G. (2017). Teaching Conceptual Metaphors to EFL Learners in the European Space of Higher Education. *European Journal of Applied Linguistics*, *5*(1), 87–114. https://doi.org/10.1515/eujal-2015-0036

Phillips Galloway, E., Qin, W., Uccelli, P., & Barr, C. D. (2020). The role of cross-disciplinary academic language skills in disciplinary, source-based writing: Investigating the role of core academic language skills in science summarization for middle grade writers. *Reading and Writing*, *33*(1), 13–44.

https://doi.org/10.1007/s11145-019-09942-x

Pickering, A. (2010). *The mangle of practice: Time, agency, and science*. University of Chicago Press.

Pourcel, S., & Evans, V. (2009). *New Directions in Cognitive Linguistics*. 1–531.

Pradhan, J. B. (2018). Mathematical ideas in cultural artefacts: A metaphor for teaching of school mathematics. *International Journal of Scientific and Research Publications*, *8*(9), 335–341.

Proctor, C. P., Silverman, R. D., Harring, J. R., Jones, R. L., & Hartranft, A. M. (2020). *Teaching Bilingual Learners: Effects of a Language-Based Reading Intervention on Academic Language and Reading Comprehension in Grades 4 and 5*. *55*(1), 95–122. https://doi.org/10.1002/rrq.258

Proffitt, D. R. (2006). Distance perception. *Current Directions in Psychological Science*, *15*(3), 131–135.

Pulvermüller, F., & Fadiga, L. (2010). Active perception: Sensorimotor circuits as a cortical basis for language. *Nature Reviews Neuroscience*, *11*(5), 351–360.

Pulvermüller, F., Shtyrov, Y., Kujala, T., & Näätänen, R. (2004). Word-specific cortical activity as revealed by the mismatch negativity. *Psychophysiology*, *41*(1), 106–112.

Rahaman, J., Agrawal, H., Srivastava, N., & Chandrasekharan, S. (2018). Recombinant enaction: Manipulatives generate new procedures in the imagination, by extending and recombining action spaces. *Cognitive Science*, *42*(2), 370–415.

Ramachandran, V. S., & Hubbard, E. M. (2001). Synaesthesia—A window into perception, thought and language. *Journal of Consciousness Studies*, *8*(12), 3–34.

Read, J. (2008). Identifying academic language needs through diagnostic assessment. *Journal of English for Academic Purposes*, *7*(3), 180–190. https://doi.org/10.1016/j.jeap.2008.02.001

Redish, E. F., & Kuo, E. (2015). Language of physics, language of math: Disciplinary culture and dynamic epistemology. *Science & Education*, *24*, 561–590.

Rehman, U., Shahnawaz, M. G., Khan, N. H., Kharshiing, K. D., Khursheed, M., Gupta, K., Kashyap, D., & Uniyal, R. (2021). Depression, anxiety and stress among Indians in times of Covid-19 lockdown. *Community Mental Health Journal*, *57*, 42–48.

Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. *Annu. Rev. Neurosci.*, *27*(1), 169–192.

Robinson, L. E., Valido, A., Drescher, A., Woolweaver, A. B., Espelage, D. L., LoMurray, S., Long, A. C., Wright, A. A., & Dailey, M. M. (2023). Teachers, stress, and the COVID-19 pandemic: A qualitative analysis. *School Mental Health*, *15*(1), 78–89.

Ryoo, K. (2015). Teaching Science Through the Language of Students in Technology-Enhanced Instruction. *Journal of Science Education and Technology*, *24*(1), 29–42. https://doi.org/10.1007/s10956-014-9518-4

Ryoo, K., Bedell, K., & Swearingen, A. (2018). Promoting Linguistically Diverse Students' Short-Term and Long-Term Understanding of Chemical Phenomena Using Visualizations. *Journal of Science Education and Technology*, *27*(6), 508–522. https://doi.org/10.1007/s10956-018-9739-z

Ryoo, K., & Linn, M. C. (2012). Can dynamic visualizations improve middle school students' understanding of energy in photosynthesis? *Journal of Research in Science Teaching*, *49*(2), 218–243. https://doi.org/10.1002/tea.21003

Ryoo, K., & Linn, M. C. (2014). Designing guidance for interpreting dynamic visualizations: Generating versus reading explanations. *Journal of Research in Science Teaching*, *51*(2), 147–174. https://doi.org/10.1002/tea.21128

Saban, A. (2006). Functions of Metaphor in Teaching and Teacher Education: A review essay. *Teaching Education*, *17*(4), 299–315. https://doi.org/10.1080/10476210601017386

Salam, A., Mahfud, M., & Nurhusna, N. (2018). Scientific Characteristics of Academic Texts: A Study of Systemic Functional Linguistics. *International Journal of Language Education*, 122–134. https://doi.org/10.26858/ijole.v2i2.5266

Salve, J., Khosla, K., Jindal, S., Makwana, M., & Chandrasekharan, S. (2023). *Attention in the mind's eye: Using the Navon attention task to track the way the grammatical structure of text passages modulate mental simulation of perspective*. *45*(45).

Salve, J., Narwal, A., Upadhyay, P., KK, M., & Chandrasekharan, S. (2021). *Learning to enact photosynthesis: Towards a characterization of the way academic language mediates concept formation*. *43*(43).

Salve, J., Upadhyay, P., Mashood, K., & Chandrasekharan, S. (2024). Performative Bundles: How Teaching Narratives and Academic Language Build Mental Models of Mechanisms. *Science & Education*, 1–39.

Saranraj, L., & Meenakshi, K. (2016). The influence of anxiety in second language learning: A case study with reference to engineering students in Tamil Nadu, India. *Indian Journal of Science and Technology*, *9*(42), 1–5.

Scarcella, R. (2003). *ACADEMIC ENGLISH: A CONCEPTUAL FRAMEWORK*.

Schleppegrell, M. J. (2001). Linguistic features of the language of schooling. *Linguistics and Education*, *12*(4), 431–459.

Schleppegrell, M. J. (2012). Academic Language in Teaching and Learning: Introduction to the Special Issue. *The Elementary School Journal*, *112*(3), 409–418. https://doi.org/10.1086/663297

Schleppegrell, M. J., & Oteíza, T. (2023). Systemic functional linguistics: Exploring meaning in language. In *The Routledge Handbook of Discourse Analysis* (2nd ed.). Routledge.

Schubotz, R. I. (2007). Prediction of external events with our motor system: Towards a new framework. *Trends in Cognitive Sciences*, *11*(5), 211–218.

Schwartz, D. L., & Black, T. (1999). Inferences through imagined actions: Knowing by simulated doing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*(1), 116.

Schwartz, D. L., & Holton, D. L. (2000). Tool use and the effect of action on the imagination. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*(6), 1655.

Sembiante, S. F., & Tian, Z. (2021). Culturally sustaining approaches to academic languaging through systemic functional linguistics. *Language and Education*. https://www.tandfonline.com/doi/full/10.1080/09500782.2021.1896538

Setati, M., Adler, J., Reed, Y., & Bapoo, A. (2002). Incomplete journeys: Code-switching and other language practices in mathematics, science and English language classrooms in South Africa. *Language and Education*, *16*(2), 128–149.

Sfard, A. (1991). On the dual nature of mathematical conceptions: Reflections on processes and objects as different sides of the same coin. *Educational Studies in Mathematics*, *22*(1), 1–36.

Sherin, B. L. (2001). How students understand physics equations. *Cognition and Instruction*, *19*(4), 479–541.

Short, D. J., Fidelman, C. G., & Louguit, M. (2012). *Developing Academic Language in English Language Learners Through Sheltered Instruction*. *46*(2), 334–361. https://doi.org/10.1002/tesq.20

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher*, *15*(2), 4–14.

Siffrinn, N. E., & Harman, R. (2019). Toward an Embodied Systemic Functional Linguistics Pedagogy. *TESOL Quarterly*, *53*(4), 1162–1173.

Sinha, R., Swanson, H., Clarke-Midura, J., Shumway, J. F., Lee, V. R., & Chandrasekharan, S. (2023). *From embodied doing to computational thinking in kindergarten: A punctuated motor control model*. 1–10.

Snow, C. (1983). Literacy and language: Relationships during the preschool years. *Harvard Educational Review*, *53*(2), 165–189.

Snow, C. E. (2010). Academic Language and the Challenge of Reading for Learning About Science. *Science*, *328*(5977), 450–452. https://doi.org/10.1126/science.1182597

Snow, C. E., Lawrence, J. F., & White, C. (2009). Generating Knowledge of Academic Language Among Urban Middle School Students. *Journal of Research on Educational Effectiveness*. https://doi.org/10.1080/19345740903167042

Snow, C. E., & Matthews, T. J. (2016). Reading and Language in the Early Grades. *The Future of Children*, *26*(2), 57–74. https://doi.org/10.1353/foc.2016.0012

Snow, C. E., & Uccelli, P. (2009). The challenge of academic language. *The Cambridge Handbook of Literacy*, *112*, 133.

Södervik, I., Virtanen, V., & Mikkilä-Erdmann, M. (2015). Challenges in understanding photosynthesis in a university introductory biosciences class. *International Journal of Science and Mathematics Education*, *13*, 733–750.

Spivey, M. J., & Geng, J. J. (2001). Oculomotor mechanisms activated by imagery and memory: Eye movements to absent objects. *Psychological Research*, *65*(4), 235–241. https://doi.org/10.1007/s004260100059

Stake, R. (1995). *Case study research*. Springer.

Suchman, L. A. (1987). *Plans and situated actions: The problem of human-machine communication*. Cambridge university press.

Talmy, L. (1983). How Language Structures Space. In H. L. Pick & L. P. Acredolo (Eds.), *Spatial Orientation* (pp. 225–282). Springer US. https://doi.org/10.1007/978-1-4615-9325-6_11

Talmy, L. (2000). *Toward a cognitive semantics: Concept structuring systems* (Vol. 1). MIT press. https://books.google.com/books?hl=en&lr=&id=DS4TDgAAQBAJ&oi=fnd&pg=PP1&dq=Talmy,+L.+(2000).+Toward+a+Cognitive+Semantics.+MIT+Press.&ots=1zRTO63jMO&sig=ybgEonkvaRhcC2xLdXvwyEPxbxg

Talmy, L. (2007). 16. The Relation of Grammar to Cognition. *The Cognitive Linguistics Reader*, 481–544.

Taylor, J. R., & Littlemore, J. (2014). *The Bloomsbury Companion to Cognitive Linguistics*. 1–416.

Tellis, W. (1997). Application of a case study methodology. *The Qualitative Report*, *3*(3), 1–19.

Thiele, R. B., & Treagust, D. F. (1994). An interpretive examination of high school chemistry teachers' analogical explanations. *Journal of Research in Science Teaching*, *31*(3), 227-242.

Treagust, D., Chittleborough, G., & Mamiala, T. (2003). The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education*, *25*(11), 1353–1368.

Truckenmiller, A. J., Park, J., Dabo, A., & Newton, Y.-C. W. (2019). Academic Language Instruction for Students in Grades 4 Through 8: A Literature Synthesis. *Journal of Research on Educational*

Effectiveness. https://www.tandfonline.com/doi/full/10.1080/19345747.2018.1536773

Tulving, E., & Thomson, D. M. (1973). Encoding specificity and retrieval processes in episodic memory. *Psychological Review*, *80*(5), 352.

Turner, M. (2007). *Frame Blending*. https://papers.ssrn.com/abstract=1321302

Tursunovich, R. I. (2022). ON THE CONCEPTUAL METAPHOR: MAN IS UP, WOMAN IS DOWN. *Proceedings of International Conference on Modern Science and Scientific Studies*, *1*(2), Article 2.

Uccelli, P., Barr, C. D., Dobbs, C. L., Galloway, E. P., Meneses, A., & Sánchez, E. (n.d.). *ACADEMIC LANGUAGE DEVELOPMENT*.

Uccelli, P., Dobbs, C. L., & Scott, J. (2013). Mastering Academic Language: Organization and Stance in the Persuasive Writing of High School Students. *Written Communication*, *30*(1), 36–62. https://doi.org/10.1177/0741088312469013

Uccelli, P., Galloway, E. P., Barr, C. D., Meneses, A., & Dobbs, C. L. (n.d.). *Beyond Vocabulary: Exploring Cross-Disciplinary Academic-Language Proficiency and Its Association With Reading Comprehension*. https://doi.org/10.1002/rrq.104

Upadhyay, P., Salve, J., KK, M., & Chandrasekharan, S. (2023). *Teacher Cognition: A Model of How Teachers Build Distributed and Enactive Narratives, to Generate and Finetune Mechanism Concepts in Student Minds*. *45*(45).

Upadhyay, P., Salve, J., Mashood, K., & Chandrasekharan, S. (2021). *Teacher enaction: Modeling how teachers build new mechanism concepts in students' minds*. *8*.

Upadhaya, B., & Sudharshana, N. P. (2021). Designing and Using Tasks to Foster Metaphoric Competence Among Learners in Indian Contexts. In N. P. Sudharshana & L. Mukhopadhyay (Eds.), *Task-Based Language Teaching and Assessment: Contemporary Reflections from Across the World* (pp. 183–203). Springer Nature Singapore. https://doi.org/10.1007/978-981-16-4226-5_10

Valdés, G. (2004). Between Support and Marginalisation: The Development of Academic Language in Linguistic Minority Children. *International Journal of Bilingual Education and Bilingualism*. https://doi.org/10.1080/13670050408667804

Van den Eynde, S., Goedhart, M., Deprez, J., & De Cock, M. (2023). Role of graphs in blending physical and mathematical meaning of partial derivatives in the context of the heat equation. *International Journal of Science and Mathematics Education*, *21*(1), 25–47.

Van den Eynde, S., Schermerhorn, B. P., Deprez, J., Goedhart, M., Thompson, J. R., & De Cock, M. (2020). Dynamic conceptual blending analysis to model student reasoning processes while integrating mathematics and physics: A case study in the context of the heat equation. *Physical Review Physics Education Research*, *16*(1), 010114.

Varela, F. J., Thompson, E., & Rosch, E. (2017). *The embodied mind, revised edition: Cognitive science and human experience*. MIT press.

Vervaeke, J., & Kennedy, J. M. (2004). Conceptual Metaphor and Abstract Thought. *Metaphor and Symbol*, *19*(3), 213–231. https://doi.org/10.1207/s15327868ms1903_3

Vygotsky, L. S. (1980). *Mind in Society: Development of Higher Psychological Processes* (M. Cole, V. Jolm-Steiner, S. Scribner, & E. Souberman, Eds.). Harvard University Press. https://doi.org/10.2307/j.ctvjf9vz4

Wang, H.-H. (2014). A case study on design with conceptual blending. *International Journal of Design Creativity and Innovation*. https://www.tandfonline.com/doi/abs/10.1080/21650349.2013.830352

Wexler, M., Kosslyn, S. M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition*, *68*(1), 77–94.

Wilson, N. L., & Gibbs Jr, R. W. (2007). Real and imagined body movement primes metaphor comprehension. *Cognitive Science*, *31*(4), 721–731.

Windschitl, M. (2002). Framing Constructivism in Practice as the Negotiation of Dilemmas: An Analysis of the Conceptual, Pedagogical, Cultural, and Political Challenges Facing Teachers. *Review of Educational Research*, *72*(2), 131–175. https://doi.org/10.3102/00346543072002131

Windschitl, M. (2003). Inquiry projects in science teacher education: What can investigative experiences reveal about teacher thinking and eventual classroom practice? *Science Education*, *87*(1), 112–143. https://doi.org/10.1002/sce.10044

Windschitl, M. (2004). Folk theories of "inquiry:" How preservice teachers reproduce the discourse and practices of an atheoretical scientific method. *Journal of Research in Science Teaching*, *41*(5), 481–512. https://doi.org/10.1002/tea.20010

Windschitl, M., & Andre, T. (1998). Using computer simulations to enhance conceptual change: The roles of constructivist instruction and student epistemological beliefs. *Journal of Research in Science Teaching*, *35*(2), 145–160. https://doi.org/10.1002/(SICI)1098-2736(199802)35:2<145::AID-TEA5>3.0.CO;2-S

Windschitl, M., & Sahl, K. (2002). Tracing Teachers' Use of Technology in a Laptop Computer School: The Interplay of Teacher Beliefs, Social Dynamics, and Institutional Culture. *American Educational Research Journal*, *39*(1), 165–205. https://doi.org/10.3102/00028312039001165

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, *92*(5), 941–967. https://doi.org/10.1002/sce.20259

Windschitl, M., Thompson, J., Braaten, M., & Stroupe, D. (2012). Proposing a core set of instructional practices and tools for teachers of science. *Science Education*, *96*(5), 878–903. https://doi.org/10.1002/sce.21027

Wohlschläger, A. (2001). Mental object rotation and the planning of hand movements. *Perception & Psychophysics*, *63*(4), 709–718.

Wolpert, D. M., & Kawato, M. (1998). Multiple paired forward and inverse models for motor control. *Neural Networks*, *11*(7–8), 1317–1329.

Yazan, B. (2015). Three Approaches to Case Study Methods in Education: Yin, Merriam, and Stake. *The Qualitative Report*. https://doi.org/10.46743/2160-3715/2015.2102

Yee, E., Chrysikou, E. G., Hoffman, E., & Thompson-Schill, S. L. (2013). Manual experience shapes object representations. *Psychological Science*, *24*(6), 909–919.

Yee, S. P. (2017). Students' and Teachers' Conceptual Metaphors for Mathematical Problem Solving. *School Science and Mathematics*, *117*(3–4), 146–157. https://doi.org/10.1111/ssm.12217

Yin, R. K. (2003). Designing case studies. *Qualitative Research Methods*, *5*(14), 359–386.

Young, H. D., Freedman, R. A., & Ford, A. L. (2008). *Sears and Zemansky's university physics* (Vol. 1). Pearson education.

Zwaan, R. A., Stanfield, R. A., & Yaxley, R. H. (2002). Language Comprehenders Mentally Represent the Shapes of Objects. *Psychological Science*, *13*(2), 168–171. https://doi.org/10.1111/1467-9280.00430

Zwaan, R. A., Taylor, L. J., & De Boer, M. (2010). Motor resonance as a function of narrative time: Further tests of the linguistic focus hypothesis. *Brain and Language*, *112*(3), 143–149.

Zwiers, J. (2006). Integrating academic language, thinking, and content: Learning scaffolds for non-native speakers in the middle grades. *Journal of English for Academic Purposes*, *5*(4), 317–332.

https://doi.org/10.1016/j.jeap.2006.08.005

Zwiers, J. (2007). Teacher practices and perspectives for developing academic language. *International Journal of Applied Linguistics*, *17*(1), 93–116.

Appendix 1: Consent Form

Date

Dear Parent or Guardian:

I am a research scholar at the Homi Bhabha Centre for Science Education, TIFR, Mumbai. I am conducting a research project on understanding students' difficulty with making sense of the language used in the textbook, which we call academic language (AL). More specifically, we want to understand how the language in the textbook affects the attention of the reader, in comparison to a more free flowing version of the same language. I request permission for your child to participate in this study.

The study consists of a letter identification task, and reading of a textbook passage. The entire study would be conducted online. The project will be explained in terms that your child can understand, and your child will participate only if he or she is willing to do so. Only I and members of the research staff will have access to information from your child. At the end of the study, children's responses will be reported only as group results.

Participation in this study is completely voluntary. Your decision whether or not to allow your child to participate will not affect the services normally provided to your child by the school. Your child's participation in this study will not lead to the loss of any benefits to which he or she is otherwise entitled. Even if you give your permission for your child to participate, your child is free to refuse to participate. If your child agrees to participate, he or she is free to end participation at any time. You and your child are not waiving any legal claims, rights, or remedies because of your child's participation in this research study.

Any information that is obtained in connection with this study and that can be identified with your child will remain confidential and will be disclosed only with your permission or as required by law. Confidentiality will be maintained by means of using pseudonyms instead of your child's name and wherever possible only group data would be presented. The data obtained during the study would be stored on a secure system for a period of 5 years after which it would be destroyed permanently. This information would be used purely for research purposes and would not be released to any other party.

The main study may be recorded and as stated above only the research team would have access to these records. These records will remain confidential and would not be shared or the identity of your child would not be revealed to any other party without your permission. There is no expectation of a student completing an assignment, and it will not affect any grade received for completing it or by not participating in the study.

Should you have any questions or desire further information, please email me at joseph@hbcse.tifr.res.in. or Dr. Mashood K.K. at mashood@hbcse.tifr.res.in. Keep this letter after completing the bottom portion and return the letter signed form with your child, which will be collected at school or you can also leave the letter signed form with your child's class teacher. We would also make this consent form available online as a google form, and would be circulated through your classroom whatsapp group. Kindly note that if the signed consent form does not reach us before the study, we cannot consider your child for participation in the study.

If you have any questions about your rights as a research subject, you may contact The Homi Bhabha Centre for Science Education, Institutional Review Board (IRB) by e-mail at irb@hbcse.tifr.res.in

Sincerely,

Joseph Salve,

Research Scholar, HBCSE

Please indicate whether or not you wish to allow your child to participate in this project by checking one of the statements below, signing your name and returning the letter signed form with your child, which will be collected at school or you can also leave the letter signed form with your child's class teacher. Sign both copies and keep one for your records.

_____ I grant permission for my child to participate in the study aimed at understanding how the language in the textbook affects the attention of the reader in comparison to a more free flowing version of the same language

_____ I do not grant permission for my child to participate in the study aimed at understanding how the language in the textbook affects the attention of the reader in comparison to a more free flowing version of the same language

Signature of Parent/Guardian	Printed Parent/Guardian Name
Printed Name of Child	Date