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ARTICLE

What Is the Role of the Body in Science Education? A Conversation Between Traditions

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Abstract

Bodily engagement with the material and sociocultural world is ubiquitous in doing and learning science. However, science education researchers have often tended to emphasize the disembodied and nonmaterial aspects of science learning, thereby overlooking the crucial role of the body in meaning-making processes. While in recent years we have seen a turn towards embracing embodied perspectives, there persist considerable theoretical and methodological differences within research on embodiment in science education that hamper productive discourse. What is needed is a careful examination of how different traditions and disciplines, among them philosophy, social semiotics, and cognitive science, bear on embodiment in science education research. This paper aims to explore and articulate the differences and convergences of embodied perspectives in science education research in the form of a dialogue between three fictitious personas that stand for the cognitive, social-interactionist, and phenomenological research traditions. By bringing these traditions into dialogue, we aim to better position the role of the body in the science education research landscape. In doing so, we take essential steps towards unifying terminology across different research traditions and further exploring the implications of embodiment for science education research.

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1 Introduction

Bodily engagement with the material and sociocultural world is ubiquitous in doing and learning science. Such engagement can take the form of gestures that prompt idea construction (Scherr, 2008; Steier & Kersting, 2019), embodied performances that bring forth scientific phenomena (Hardahl et al., 2019; Keifert et al., 2021), the orchestration of embodied actions and material objects that create evidence during scientific inquiry (Tang, 2022), or embodied metaphors that support making sense of abstract concepts (Amin, Jeppsson & Haglund, 2015; Close & Scherr, 2015; Kersting & Steier 2018). In response to this variety of embodied science learning, researchers have become increasingly interested in explicitly adopting embodied and material perspectives in science education (e.g., Amin et al., 2015; Hardahl et al., 2019; Euler, Rådahl, & Gregorcic, 2019; Kersting et al., 2021; Macrine & Fugate, 2021; Tang, 2022; Weisberg & Newcombe, 2017). This turn towards embracing embodied perspectives breaks with a long tradition of emphasizing the disembodied and nonmaterial aspects of science learning. Indeed, science can be considered a school subject with a history and culture of separating body and mind (Almqvist & Quennerstedt, 2015; Alsop, 2011; Hardahl, 2019).

While a greater focus on the body promises to provide a more holistic account of scientific meaning-making processes, research on embodiment in science education is still an emerging field and far from established. Therefore, approaches to conceptualizing the body in science education research have remained fragmented across different academic traditions—and often appear isolated from more established theoretical perspectives in science education. Consequently, considerable theoretical and methodological differences persist within the research on embodiment in science education, hampering productive discourse around the topic (Kersting et al., 2021). Likewise, there are many ways of translating theoretical insights of embodiment research into science education practices. Each tradition will offer different answers to how students can think about and learn science in embodied ways.

What is needed is a careful examination of how different traditions and disciplines, notably philosophy, cognitive science, and social semiotics, bear on embodiment and have inspired research in science education. Understanding the diversity of embodied perspectives will also help practitioners tap the full potential of embodiment in science teaching and learning. Thus, this paper aims to explore and articulate the differences and convergences of embodied perspectives in science education research and map out routes to further progress in the field. We unpack our joint exploration of embodiment in the form of a dialogue between three fictitious personas that stand in for the cognitive, social-interactionist, and phenomenological research traditions. These traditions have provided crucial perspectives on how we navigate, experience, and understand the world as embodied beings (Kersting et al., 2021). Each has promoted distinct stances on science learning and spurred productive research in science education.[1] We use the three personas to discuss the role of the body in science education from their respective vantage points, thereby carving out overlap, complementarity, and synergies regarding embodiment across different

[1] We acknowledge that we are being selective in our choice of traditions. Other philosophical traditions, notably Dewey's pragmatism (Dewey, 1910; Dewey & Bentley, 1949), have had a lasting influence on science education research and practice (Toscano & Quay, 2021). In recent years, science education scholars have also paid more attention to a growing "new materialism" paradigm (Hetherington et al., 2018; Milne & Scantlebury, 2019; Tang, 2022). Common to these traditions is the commitment to knowledge as situated in action, which we also find in the phenomenological and social-interactionist traditions that feature in our dialogue.

traditions. We have chosen the dialogue format as a rhetorical tool to give voice to the different traditions and thereby allow their respective personas to challenge each other, seek to understand each other, and co-create a greater appreciation of the differences and convergences between their standpoints. In doing so, we add this paper to a canon of rhetorical dialogues composed by philosophers and scientists, among them Plato (Jowett, 1911), Galileo (1967), Feyerabend (1991), and, more recently, scholars from science education research and the learning sciences (Roth et al., 1998; Wise & Schwarz, 2017).

In our view, part of the problem of the theoretical and methodological fragmentation that we currently see in science education research is due to the use of jargon: distinct traditions can often create silos of thinking and expression, which, in turn, obstruct deeper insights that cut across these traditions. By bringing various traditions into dialogue, we aim to show that the body is already an implicit part of existing traditions and that many embodied and material aspects of science education transcend the traditional boundaries of distinct research traditions. If our community can recognize overlap in our constructs and signal that overlap through shared terminology, research on embodied science learning is likely to be more cumulative (Amin & Levrini 2018).

1.1 Our Approach

Naturally, there are many different ways of locating the body in science education, and perspectives may range from the neural underpinnings of sensorimotor experience and its contribution to conceptual understanding (Amin, 2021) to the ontological inseparability of cognition and material culture (Malafouris, 2013). To narrow down the scope of our conversation between traditions, we have chosen to focus our attention on an already published piece of data, namely a transcript of a short episode where two secondary school students engage in an embodied dance as a metaphor for the motion of binary stars (which originally appeared in Euler et al., 2019). This episode acts as a conversation catalyst and structures our shared explorations of embodied and material perspectives. During the conversation, the three personas reanalyze and discuss this episode to illustrate their stances on science learning and their understanding of the body in the context of science education.

The writing process of this manuscript involved many rounds of conversation and role-playing by the authors as we jointly analyzed the shared episode. We recorded these real conversations that we conducted over Zoom over the course of a year. Each conversation was transcribed, and we constructed the dialogue in this manuscript by drawing on and reworking elements of these transcribed conversations iteratively. The personas are written to express genuine interest and curiosity in alternative perspectives. We thus hope that the conversation more closely resembles a productive conversation between three real educational researchers from different traditions rather than the parallel expression of three monolithic voices. Of course, we acknowledge that real people do not speak using references, parentheses, and footnotes. However, our dialogue still constitutes an academic text. We believe that we have struck a good balance between stylistic features of oral conversations and academic writing: while our dialogue retains some informality, interactivity, and unpredictability (e.g., interruptions, sudden changes of topic, repetitions) that are characteristic of spoken language, we have added references and some more specialized vocabulary to provide readers with an appropriate introduction to the three traditions.

It is important to note that the three personas are not intended to depict generic versions of their respective traditions. Rather, they are written as reflections of the authors' own diverse specific views of these traditions, with the main goal of creating opportunities for

dialogue and contrast. Moreover, our personas are not philosophers or cognitive scientists but educational researchers who have a genuine interest in impacting and improving educational practices. We believe there is value in giving voice to practicing science educators and educational researchers to ground lofty discussions on embodiment in the educational realities of science teaching and learning. Acknowledging the distinctive perspectives and practical experiences of science educators can lead to a more nuanced and accurate understanding of the role of the body in science education and the relationship between embodiment and science learning.

2 Setting the Scene

In the following, we first set the scene by introducing the episode and the three personas. We then present the conversation between traditions in five acts. These acts roughly follow the classic dramatic structure to address embodiment issues and conflicts between the traditions. In negotiating these conflicts, the personas stay close to the dancing episode, which serves as a narrative anchor and helps clarify the role of the body in each conflict. Since the goal of the conversation is not necessarily mutual agreement but a shared understanding of each other's perspectives, the conversational tone between the characters stays open and friendly.

2.1 The Dancing Episode

The starting point of our conversation between traditions is an already published transcript of an episode analyzed in detail in a previous study (Euler et al., 2019)—though with a different research agenda. In the episode, two Swedish secondary school students, Beth and Adam, explore the motion of binary stars on an interactive whiteboard (Figs. 1, 2, 3, 4, 5). The students volunteered to participate in a 2-h session where they received a short introduction to the software and explored the movement of bodies in orbital motion. One researcher stayed with them throughout the activity to provide technical support and encourage discussions when the students were stuck.

A major focus of the original paper is exploring the congruencies between disciplinary-relevant aspects of binary star mechanics and students' spontaneous embodied ways of meaning-making. The authors identify four disciplinary-relevant aspects of formal knowledge that are required to explain the orbital motion of the binary star system: (1) the orbital phenomenon of the binary system involves the interaction of two bodies,[2] (2) the two bodies are interacting reciprocally with one another, (3) the interaction of the bodies with one another determines their motion, and (4) the interaction is attractive. These four aspects qualitatively describe specific facets of Newton's laws. The authors show how students' ideas expressed and developed through their embodied interactions can be traced to the facets of Newtonian mechanics. For example, the embodied analogy of a partner dance, where two partners have unequal mass, allows Beth to appreciate the

[2] In the context of Newtonian physics, a *body* means a real or idealized object with defined borders between itself and the surroundings, such as an astronomical body (e.g., a star), not necessarily a human body. Still, a human body can also be a physical object of interest and thus a *body* in the physics sense of the term.

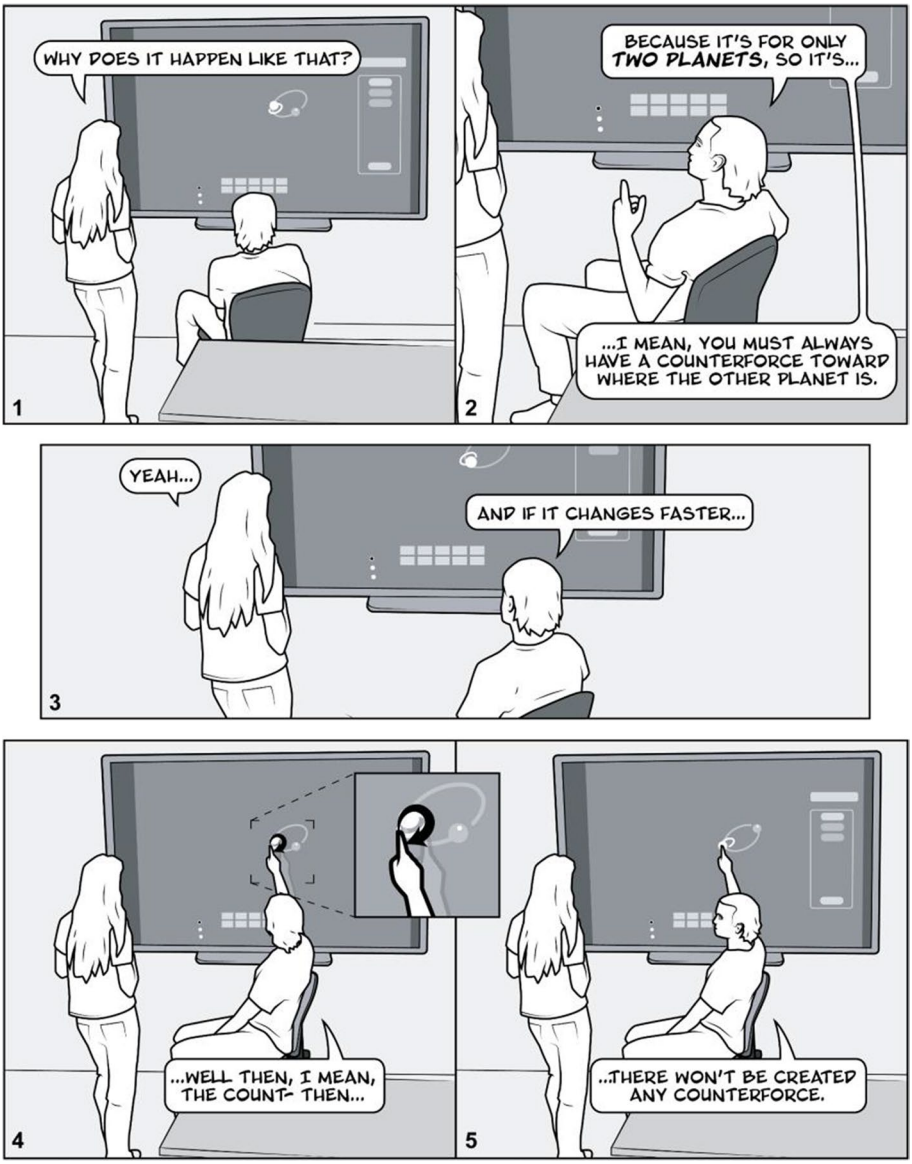

Fig. 1 An illustration of Adam and Beth, who explore the orbital movement of stars on an interactive whiteboard

reason for her (and the analogous, less massive star) having a larger orbit than her more massive partner (frames 28, 29, and 30 in Fig. 5). This pattern, which appeared intuitively understandable to Beth, can also be explained using Newton's laws of motion or the law of conservation of momentum. We would like to point out that the focus of the

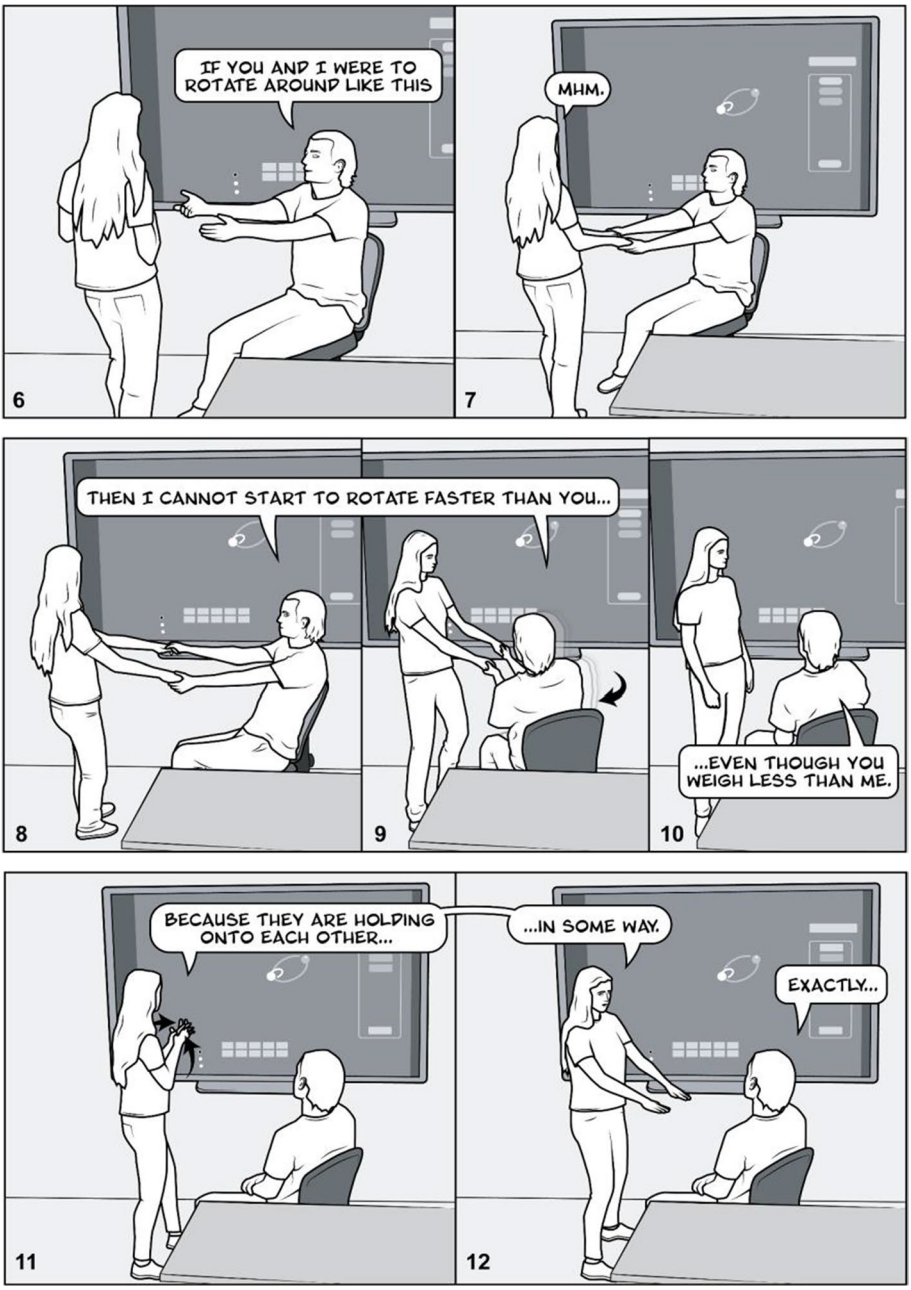

Fig. 2 Adam and Beth engage in an embodied dance to make sense of the orbital movement of stars

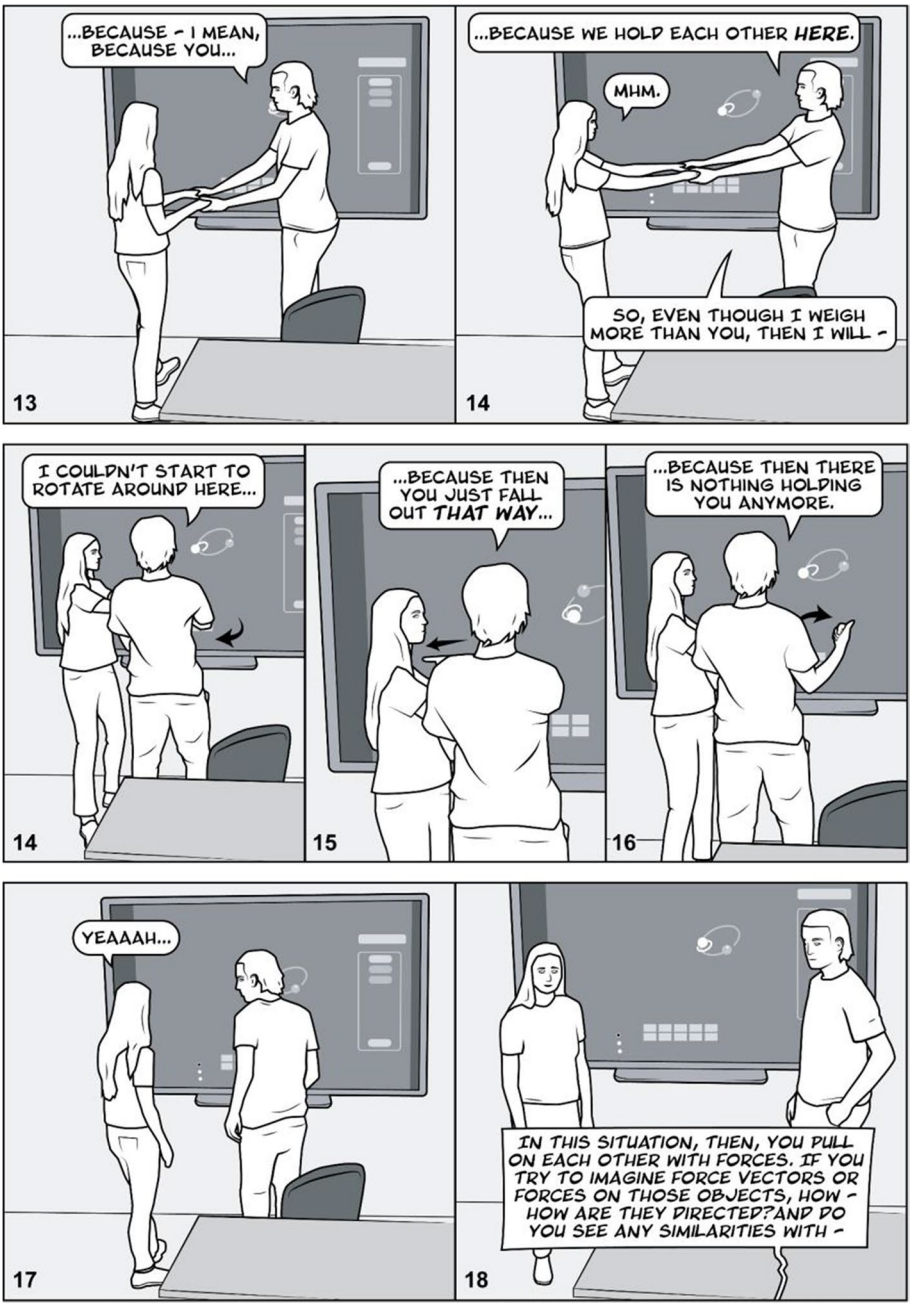

Fig. 3 Adam and Beth discuss what it takes to rotate around each other

present paper lies not in unpacking the subtleties of the conceptual mapping between students' interactions and the laws of physics,[3] or demonstrating instances of productive

[3] For such an analysis, see the original paper by Euler et al. (2019).

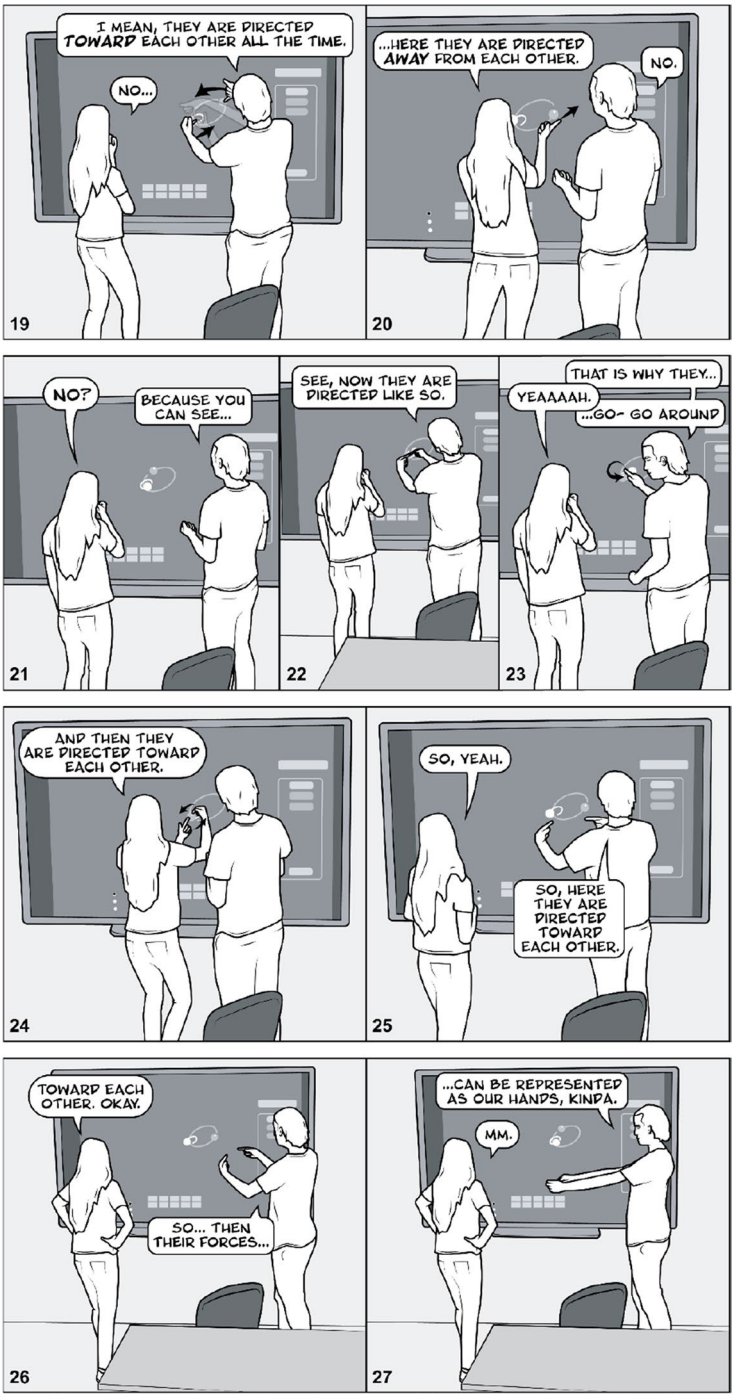

Fig. 4 Adam and Beth explore the direction of forces in the orbital movement

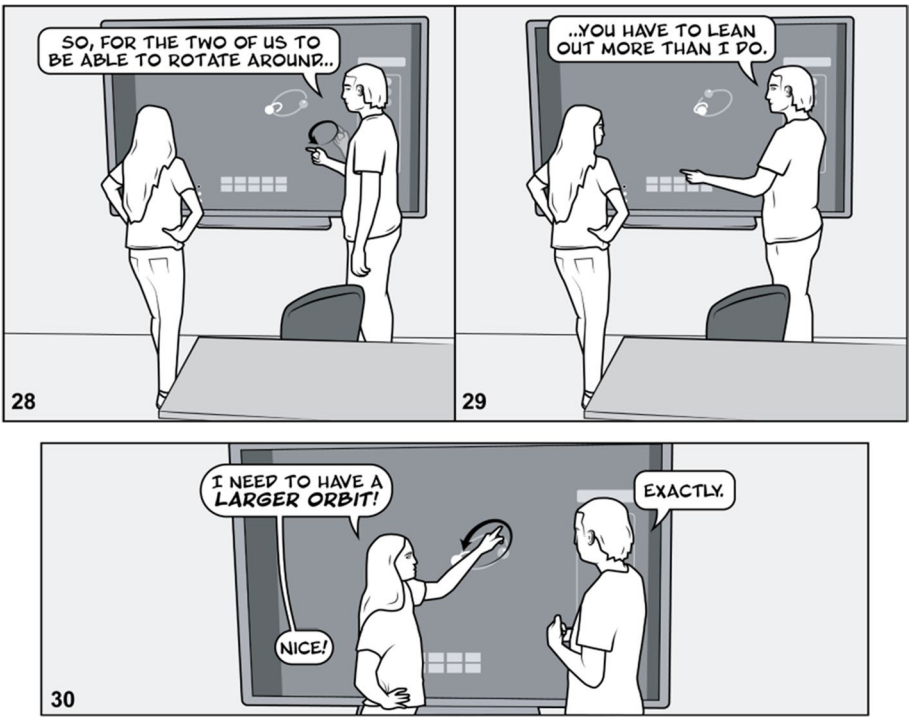

Fig. 5 Beth has the crucial insight that she needs a larger orbit to be able to rotate around Adam

learning, but rather in illustrating how different traditions may see the role of the students' bodies in the presented episode.

2.2 Dramatis Personae

2.2.1 The Cognitivist

As a cognitivist, I seek to characterize thought and learning functionally in terms of generalizable cognitive models to make sense of patterns in behavior. Usually, I put forward models that specify the information represented in the mind, the format of representations, and how these are manipulated to generate new representations. While this has not always been the case, I now understand the body as an important player in mental processes, and I subscribe to the so-called "embodied cognition" perspective (Gibbs, 2005; Lakoff & Johnson, 1999; L. Shapiro, 2014). I no longer find it appropriate to abstract away from the body when characterizing thinking, as if any machine can do the kind of thinking we do. I believe that the specifics of the human brain, the human body, and the material and symbolic tools used to perform human tasks must be considered when we construct models——even models of reasoning with abstract scientific concepts. In other words, I subscribe to what Kersting et al. (2021) refer to as a "physical sense" of embodiment**.**

2.2.2 The Social-Interactionist

As a social-interactionist, I follow scholars like Jay Lemke (1990), Jean Lave (1991), and Charles Goodwin (2000) by looking for learning in social situations where people are collaborating and working together in dialogue and for the ways that their shared understandings are reflected in shared representations. I understand the body as a site for expressing shared representations, coordinating action, and interacting with the physical and material setting. In other words, I subscribe to an interactionist sense of embodiment (Kersting et al., 2021). An important aspect of my perspective is that we cannot remove either individual from the setting and see the same expression of understanding—as it is mutually elaborated. Embodiment is all about communication and interaction in a particular situation. Studying embodiment is relevant because it gives insights into the *process* of meaning-making. For me, the "in-between bits" are more interesting than the pre- and post-states of knowledge.

2.2.3 The Phenomenologist

As a phenomenologist, I follow scholars like Merleau-Ponty (1962), Heidegger (1962), and Husserl (1965) to position the learner as an embodied and participating subject at the core of (scientific) knowledge production. It seems clear to me that knowing and perceiving are connected to our being and acting in the world. Thus, I think it is essential to reject dichotomies between the subject and object—and between the mind and the world. For me, the purpose of phenomenology is to uncover how subjective experiences assist in meaning-making processes. I do not understand the body as a kind of objective vehicle for abstract thinking. Instead, I believe *knowing is being*. That is, thinking is, above all, thinking through the body. We cannot perceive objectively since our perception is always connected to our bodies and lived experiences. When we study embodiment, we situate learning in the lived body by asking *whose* actions we are looking at: it is always SOMEbody engaging with the world (Hardahl, 2019). In short, perception is realized through a living feeling body, and I subscribe to what Kersting et al. (2021) refer to as a phenomenological sense of embodiment.

3 Act I

In which the personas introduce their stance toward learning and explain what they pay attention to when they look at the dancing episode.

Cognitivist: So, shall I go first?

Interactionist: Please do. I'm interested to see how you get us started.

Cognitivist: Thanks! Well, let me start by putting my cards on the table and give you a sense of the theoretical assumptions I bring to this discussion of the episode we've agreed to reflect on together.

Phenomenologist: Good idea.

Cognitivist: OK, here goes. For me, learning can be understood as changes in knowledge structures. Knowledge of the world is described in terms of representations… I seem to have already lost you, Phenomenologist, before I've even gotten started.

Phenomenologist: Sorry, I didn't think you'd notice that. That was a very subtle movement of the eyebrow. Don't be so sensitive. Please go on.

Cognitivist: I guess I am feeling a little touchy. As a cognitivist in a discussion on the role of the body in science education, I feel I have more to prove than the two of you. I know the historical baggage that I bring to the table as a cognitivist. Traditional cognitivists like Jerry Fodor or Herbert Simon would have insisted that knowledge is represented in terms of arbitrary, mental symbols. But let me reassure you quickly that I actually subscribe to the perspective of embodied cognition; I recognize that a lot of knowledge is represented in the form of iconic/analogical representations emerging from sensorimotor experience. I also acknowledge that knowledge is not just mental or "in the head;" knowledge is also distributed over external, public representations. I understand learning as transformations in knowledge structures represented both mentally *and* in terms of public representations.

Interactionist: Great to hear! So there are some points of contact between our views that I see already. But don't let me interrupt you. Go on.

Cognitivist: Thanks for that, Interactionist. That remark helped me settle into this a bit. So let me tell you then what I am looking for in this episode; I look for patterns in the observed behavior to hypothesize a model that can explain how the task is performed, drawing on internal and external representations of various kinds. I would ask questions like: What knowledge structures do Adam and Beth possess? How did that guide their decision to engage in this dance, and how do they apply knowledge structures to make inferences from it about orbital motion? What cognitive processes are unfolding in the minds of each individual as they participate in this embodied dance, and how do they use public representations to extend the reach and power of their mental representations? So that's my entry point. I look forward to hearing each of your takes on this.

Interactionist: Well, I'll go next. Cognitivist, you started with how you view learning. Let me start there too. For me, learning can be understood as changing patterns of participation and disciplinary fluency with semiotic resources. I don't really like to focus on the individual learner. I prefer the group or the social situation as a unit of analysis. So when *I* look at this episode, I wonder how the students used their bodies and dance to make sense of orbital motion. But what's key for me is to ask how the dance emerged as a shared representation. I also ask: how did the students select this representation and coordinate it with other resources for meaning-making? And—to use a word I like a lot—I ask: what social *affordances* do the embodied postures and bodily interactions between Adam and Beth provide?

Phenomenologist: As for me, learning is best understood as students' engagement with and adaptation to the world. When I say "world," I want to capture a wide range of things: space, objects, people, culture, structures, and so forth. Yet, building on philosopher Maurice Merleau-Ponty (1962),—and this may surprise you given the topic of our discussion—learning is actually not at the forefront of my agenda. I build on a view of the body as conditional for perception and adaptation to the environment (call that learning if you want) as something that is pre-reflective in nature and thus highly tacit. For that reason, I am interested in establishing how our bodies and embodied practices shape how we come to know the world and its objects, not how this knowledge is reflected, and the relationship between body and consciousness, or experience and reflection (Knudsen, 2009). Therefore, my unit of analysis is the body and its movements as expressions of knowledge.

Cognitivist: This is very interesting. I'm glad we're airing our core commitments early in this conversation.

Phenomenologist: I agree. This was an important place to start. So, as for this episode, when I look at it, I wonder about the lived and subjective experiences of Beth and Adam,

how they encounter each other, and the situation they are in. I ask, for example, how do each of them engage with the physical objects and each other, and how are their actions expressions of knowing? What kind of habits and repertoires of action do they associate with the situation/room? Does the activity in this setting call for what Crossley (2007) calls "body techniques" that are available to Beth and Adam? Do these techniques allow Beth and Adam to embody meaning through action? In other words, how do their actions tell me something about who they are and how this impacts how they come to know and learn about science?

Interactionist: A fascinating beginning. I have lots of questions. I look forward to unpacking all this further.

4 Act II

In which the personas discuss their units of analysis and the role of the body in their analytical approaches. We see clear differences between the cognitivist approach (focus on individuals), the interactionist approach (focus on group performance), and the phenomenological approach (focus on the relational nature of minds, bodies, and the world).

Interactionist: I think it was very important to get our major theoretical commitments on the table early. But the devil is often in the details. So let's look more carefully at this cool episode we agreed to discuss! To me, what's so special about this episode is that we can see the emergence of a performed model that takes two people with two bodies to produce. I brought up the issue of the unit of analysis earlier; it's already clear from our discussion that our units of analysis differ. I feel that taking the *group* as the unit is really well suited to exploring what's happening here. The dance between Adam and Beth is not a resource that exists already, and it doesn't appear to be a model from a textbook either. It starts with a verbal discussion, and the question by Beth, "Why does it happen like that?" (frame 1) prompts the exploration of the ideas, which I would say is mutually embodied. From an interactionist perspective, each statement is best understood in relation to others and in sequence; each utterance is situated as a response to what came before it and the context in the room. Just look at how these students are learning together with their bodies!

Phenomenologist: I really like how you push for a broader unit of analysis that encompasses more than just one body, Interactionist! This episode illustrates nicely why minds, bodies, and the world must be considered as an inseparable unit. Isn't it fascinating to observe how Adam and Beth's bodies bring forth the possibility of meaningful engagement with physics? Clearly, learning is the emergent and relational product of material engagement (Malafouris, 2013).

Interactionist: I know! We can see so clearly how embodiment provides the condition for shared participation and meaning-making.

Cognitivist: You both seem to be very comfortable with this group-level unit of analysis, and you both seem to have no problems using the word "emergence." That way of thinking doesn't come so naturally to me, but I am trying to step out of my comfort zone a bit. And with a bit of a stretch, I can see that focusing on the two people interacting and speaking of "emergence", is, in some sense, reasonable. I can see that Adam and Beth's reasoning are not thoughts that are ready-made. The idea of holding hands, certainly, doesn't feel like it was something that either of them had thought about before – I'm comfortable saying that this emerges in that situation. But I would say that these two individuals seem to be playing

very different roles and making very different kinds of contributions to this interaction. Would you agree with that?

Phenomenologist: Maybe; I'd like to hear you unpack that a bit and see what you are implying by your question before reacting.

Cognitivist: Well, to me the degree of confidence with which they each speak and how much they contribute to the content of the dialogue is different. And based on these observations about the nature of their involvement, their role, and what they contribute, I would infer differences in their individual knowledge. This is partly why I think that the human individual is *the* or at least *one* appropriate unit of analysis when studying learning.

Phenomenologist: So, you are saying that Adam displays a more advanced understanding than Beth?

Cognitivist: Right. For Beth, the notion that motion in some direction implies a force in that direction is an intuition that seems to come in quickly. Her feeling that she is thrown outwards while they rotate hand-in-hand suggests to her that there is an outward force. That is a common misconception that is often observed in novice physics learners. It is Adam who then directs her attention to the fact that they're pulling at one another, and she's happy to go along with him and shift her thinking.

Interactionist: But I think you're too quick to start talking about misconceptions and are missing what's interesting here. The act that they both perform together contributes something very new to their thinking.

Cognitivist: I completely agree with you, Interactionist. I was actually getting to that! I was about to say that Beth shifts her thinking *because* Adam draws her attention to the fact that their interlocked hands are pulling on one another. Because Adam's idea is compelling, she seems happy to shift in that direction. The embodied experience of holding hands does seem to play a role in clarifying Adam's idea and helps Beth activate a different intuition about the situation—the inward force—which is more in line with what Adam is proposing. I really find this moment when Beth is shifting her perspective in response to Adam so interesting because it seems to be a key moment in the transformation of her knowledge – but this is triggered by Adam's invitation to hold hands and suggestion to look at this as representing forces that are pointing inwards. Don't you think Adam plays a particularly important role in this exchange, and this reflects his knowledge?

Phenomenologist: Yes, I agree, Cognitivist. We can see that Beth plays a different role than Adam at this moment. There is a certain asymmetry in the relationship between both students. But why would we solely ascribe that to their individual knowledge of physics?

Cognitivist: Please do say more; it's really hard for me to see how we can avoid it so, I really would like to hear how you would analyze this differently!

Phenomenologist: Well, this is how I would go about this. Adam and Beth enter the classroom, each embodying different ways of being in the world. The ways in which they comport themselves in the situation are expressions of how they grasp the room and the situation based on a lifetime of experiences that are nested as habits and expressed through what we can call personality. Different bodies give rise to different experiences. For example, impairments of the body, such as disability (Aggerholm, 2020), lack of physiological resources (Schnall et al., 2008), or feelings of unease, such as stomach cramps (Leder, 1990) shape our perception and, therefore, also action. This makes me wonder about the lived body of Beth, and if her willingness to follow Adam in the dance and subsequently also in the reasoning relates to how women comport themselves and move differently than men do. The everyday orientation of the body of a person toward the environment and their particular goals define the relation of the person (I would say "subject") to their world (Young, 1980). And in this, we may see evidence of the

relevance of the structures of feminine existence. I would ask: Is Beth's perception of the situation and actions she produces in it as a result of that perception *delimited* by her being a woman?

Cognitivist: That may well be true, Phenomenologist. And I grant that my lens on this situation didn't really encourage me to see Beth in those terms at all, so I appreciate that you are expanding our perspective here. Yet, you can't deny that Adam has an idea, and he guides Beth into making sense of it. I wonder how much of this guidance stems from Adam's understanding of Newton's second and third laws? Adam seems to have a sense that those laws are relevant. I would argue that that gives him an idea of how to think through the phenomenon, and then the episode unfolds consistently with the laws that he's invoked, even though he hasn't articulated that explicitly. Again, I am led to the conclusion that we can infer differences in Adam and Beth's knowledge states – and that it is useful to look at each student separately in these terms to understand what's going on.

Interactionist: I'd like to chime in here. Don't you think that assigning that activity to the cognitive state of one student or the other seems to miss out on some of the really interesting things that are happening, Cognitivist? Especially if we're interested in understanding embodiment on its own terms rather than as a proxy for internal knowledge states. For example, how do Adam and Beth combine talk, gesture, body position, and disciplinary resources to make meaning of the motion of the binary system? This meaning-making process is a joint accomplishment that can't be reduced to the individual students (Roth, 2013). You miss all of that if you just focus on one student!

Cognitivist: I can grant that there is stuff happening that's emerging in the interaction that you wouldn't want to attribute to what's happening inside of either Adam or Beth's individual minds. But ultimately, I think it's hard to understand what's going on without some inferences about what kinds of knowledge structures they each activate as individuals. I agree that once they hold hands, there is "meaning emerging in that interaction"—to use your phrasing. But "emergent meaning" here, for me, is a cover term for a complex interaction between internal mental and external embodied representations. I have lots of questions that follow from that way of thinking.

Interactionist: OK. Let us hear them!

Cognitivist: Absolutely. And as you said a few minutes ago: the devil is in the details. So here is what I would ask. What knowledge structures of Adam's led him to his imaginative insight to hold hands as a way to think through this phenomenon? What enabled Beth eventually to have the crucial insight, "*I need to have a larger orbit!*" (frame 30)? Did Adam already know some physics that helped? Did certain mental models ground his understanding of Newton's laws? When Adam says, "*You must always have a counterforce toward where the other planet is*" (frame 2), that seems to me to be a moment that is really constraining all that follows. And so, for me, a crucial question becomes: what is the role of Adam's prior knowledge of Newton's laws, and what mental models did he possess that grounded his understanding of those laws? Maybe it is those models that led to the insight—however unconscious—that holding hands would be a productive thing to do.

Phenomenologist: Hmm, I agree with Interactionist on this matter, Cognitivist. I can't shake off the impression that your account must be flawed from the start because you assume that minds, bodies, and the environment are fundamentally separable (Malafouris, 2013). My tradition starts from the ontological unity between cognition and the material world. If we take this unit apart into its constituents, the phenomenon will disappear. After all, learning is about what happens in the *encounter* between the student and the world and the actualization of meanings tied to these experiences (Jing & Jespersen, 2017). Why would you model the minds and bodies of students as closed objects separated from the

world? How can you ever provide a proper account of learning when you neglect the analytical implications of context and material interaction in your analysis?

Cognitivist: Well, you may see it that way, but I don't see myself as separating mind from context. I certainly don't mean to imply that context and interactions don't play any role in learning science. I am emphasizing the mental representations, but I do view them as interacting with what's on the interactive whiteboard and Adam and Beth's bodies as they engage in that brief dance. However, once Adam and Beth leave this situation, and they go on to other learning experiences, if we're going to say that learning happened, we might want to hypothesize what it is that they have taken away individually and carry with them in their minds; that will be represented in their minds in some form. And we would be interested in wondering about how they would apply what they take to other situations. So looking at individual students does make sense to me. Not least—and we are discussing science *education* here—because the teacher's central practical task is to assess the individual student's understanding of taught content, isn't it?

Interactionist: Our views of assessment are actually an interesting way to think about this. I might be inclined to think about group assignments or group performance as an indicator of understanding. Whereas I guess you would focus more on the individual contribution.

Cognitivist: Indeed, I would.

Phenomenologist: Oh, that's a good point, Interactionist. Just because our current educational systems emphasize individual students' understanding and skills doesn't make it the right or only way to assess science learning. It's clear to me that different conceptual stances to embodiment in science education – or lack thereof – will impact the learning culture, instructional designs, and assessment systems.

5 Act III

In which each persona gets their own scene to present their analytical approach in more detail. The interlocutors challenge each other's position to better understand the role of the body in science education.

5.1 Cognitivist's Scene

Cognitivist: Although you might not agree with me choosing individual students as my unit of analysis, let me try to bring my perspective a bit more to Adam and Beth's interaction now. And it would be good for me to be more explicit about how I see the role of the body in all this since that is what we are here to discuss. Afterward, you can tell me what you think I am missing in my take on the episode, OK?

Phenomenologist: Sounds good. Go ahead.

Cognitivist: The most compelling impression that I got from this episode concerns the many image schemas that are implied by the reasoning that is happening. So Adam and Beth are joining hands and then drawing conclusions from that about the kind of motion that they think can and cannot happen. I would ask: how does that experience of holding hands help them in their reasoning? There were places where I noticed the logical language of "if this, then that". How does their dance support reasoning like this?

Phenomenologist: Can you give an example? What do you mean by image schema exactly?

Cognitivist: Sure, for example, starting in frame 6, Adam says, "If you and I were to rotate around like this … I cannot start to rotate faster than you". There's something logically compelling to him that two linked entities rotating cannot rotate at different speeds. There seems to be a knowledge structure which I would describe as an abstracted pattern of *two linked objects engaged in a circular motion* interpreting the physical movement they are engaged in and supporting the reasoning they are doing. I would call that pattern an image schema, as the philosopher Mark Johnson (1987) and the psycholinguist Ray Gibbs (2005), and cognitive linguists generally use the term (Lakoff & Johnson, 1999).

Phenomenologist: Just to clarify quickly: is there a connection between these image schemas and the body? You do talk about an embodied basis for cognitive structures, right?

Cognitivist: Right. I think it makes a lot of sense to assume that our cognitive systems rely on structures that emerge from body-based experiences. Embodied experiences (often in the form of repeated patterns of sensorimotor experiences) give rise to "phenomenological building blocks" of cognition – and we often call these building blocks image schemas following the authors I just mentioned. So you can think of image schemas as knowledge structures that are abstracted from our sensorimotor experiences that end up playing a role in many aspects of scientific thinking and language use (Amin, 2021). I'm trying to convince you that we are seeing the manifestation of a *rotation of linked objects* image schema but also a *forced motion* image schema in this episode.

Phenomenologist: Oh, your reference to forced motion reminded me of Andy diSessa's work; is there a relationship between these phenomenological building blocks that you are calling image schemas and diSessa's (1993) notion of "phenomenological primitives," or 'p-prims' that he argues people develop when interacting with the environment?

Cognitivist: Yes, certainly. I actually see diSessa as a cognitivist, even if he uses the word "phenomenological." diSessa argues that students' intuitive explanations of everyday situations but also the situations they encounter when learning physics can be understood in terms of their use of p-prims. P-prims also account for students' sense of comfort with certain situations or surprise in others (Kapon & diSessa, 2012).

Phenomenologist: A bit like the surprise we see in Beth (frame 21) when Adam tells her she is wrong about the direction of force!

Cognitivist: Yes, that's right. She seems to be basing her intuition that there is an outward force on an experience-based image schema; maybe, something like the schema that I just referred to of two linked objects rotating together; that can be the source of her feeling of being "thrown" outwards.

Interactionist: I've been listening to this carefully, and I've been focusing on your use of words (you know I like to do that!); I noticed that you just slipped into using the term "image schema" after you were just talking about "p-prims." Are you using these terms interchangeably?

Cognitivist: I can't get anything by you. I actually thought you'd lost interest with all this mentalist talk of schemas and such. Actually, that's a good question, and I should have been a bit more careful and pointed this out. Some researchers view p-prims and image schemas as very similar kinds of knowledge structures (Amin, 2021b). They are both understood by the researchers that have proposed and used these constructs as schematic structures that emerge from experience in the world. While diSessa (1993) also acknowledges these similarities, he has cautioned that there are differences between these constructs. So you were right to call me on this, Interactionist. But I think these differences are not really important for our discussion here and may distract us. The main point is that when viewed from this perspective, when you are learning science, part of what you are learning is when to activate particular p-prims (or image schemas)

appropriately in particular contexts so as to explain phenomena and make predictions as a scientist would. And I believe that we see an example of such activation in our episode.

Phenomenologist: This is really interesting. Phenomenological building blocks and phenomenological primitives (I think I prefer diSessa's term) sound similar to Husserl's (1939) "primal premises." According to Husserl, we discover these primal premises as the facts of our lifeworld when growing up. So we become familiar with our surroundings where the primal premises just present themselves prior to all sciences. In my mind, image schemas, p-prims, and primal premises all point to the distinct first-person character of our bodily engagement with the material world.

Cognitivist: That is an interesting observation, Phenomenologist. By the way, I'm not familiar with Husserl's notion of primal premises; it does sound quite like the notion of p-prim. But I would even like to go one step further to bring this back to the physics learning in our episode. Beth does take an explicit first-person perspective when she says, "*I need to have a larger orbit!*" (frame 30). She is putting herself in the situation of the orbiting stars. In a sense, she is rescaling the phenomenon and imaginatively (one might say, "metaphorically") inserting herself in it, so that she can explore it in an embodied way.

Phenomenologist: I know, I know! For me, this would be a perfect starting point for a phenomenological analysis because we see so very clearly how action and perception are linked. Beth explores the physics phenomenon by engaging bodily with it.

Cognitivist: Right. Actually, the cognitivist tradition offers several analytical lenses to unpack this move. First, there is classic research in cognitive psychology that has made a case for the role of mental imagery in thought (Kosslyn, 2008), and imagery has been seen as important by cognitivists interested in creative scientific thought (Clement, 2022; Nersessian, 2008) and learning scientific concepts (Clement, 2009). Beth seems to be enacting mental imagery as a basis for her reasoning here. Also, from the point of view of conceptual blending (Fauconnier & Turner, 1998; Gregorcic & Haglund, 2021), Beth seems to draw from two different "input spaces"—to use conceptual blending terminology—in understanding this phenomenon. One input space is her and Adam engaged in a dance, and the other input space is the binary star system. When she draws selected characteristics from these input spaces to a shared blended space, new features appear when she "runs the blend " as they say, i.e., exploring a particular scenario in the blended space. In this case, the use of the pronoun "I" indicates that she imagines what it would be like to be in orbit, like a star.

Interactionist: In a similar way, Ochs et al. (1996, p. 339) recognized the use of first-person pronouns in relation to physical phenomena as an indication of "a blended identity that blurs the distinction between the two."

Cognitivist: Right. I like that paper that you're referring to. So we're reading similar articles, interesting!

Interactionist: It is interesting. I have to admit that I am surprised to see you as a cognitivist paying so much attention to the subtleties of language use, including pronouns, that are otherwise easily neglected.

Cognitivist: Well, it was only when I started to read the cognitive linguistics literature that I realized how closely and subtly connected cognitive and linguistic structures are. It would actually be fun to reflect on our trajectories as researchers and unpack what has shaped the perspectives that we bring to this discussion.

Interactionist: That would be fun, but let's leave that for another time. Let's stay focused on this episode. When I mentioned the Ochs et al. paper I felt that you were going to say more. So why don't you get back to that?

Cognitivist: Yes, you're right. I was about to say one more thing about image schemas. It's not just that Adam and Beth are feeling something while rotating around and holding each other, but they are also projecting that embodied experience onto the stars. And for that to happen, they need some abstraction away from the embodied experience, and that's what I think image schemas do for them. Image schemas serve as the source domains of conceptual metaphors which project inferences onto a situation other than the embodied situation that we are actually experiencing (Lakoff & Johnson, 2003). However, the nature of this image—that Adam ends up extending both hands to Beth, saying, *"If you and I were to rotate around like this"* (frame 6)—is triggered by the fact that he's already conceptualized the idea that there has to be a counterforce.

Interactionist: Let me see if I understand you correctly. You think we observe the projection of embodied experiences onto abstraction, and the formal knowledge constrains this process? So for you, the formal knowledge comes first, and then Adam enacts this knowledge in the form of a dance?

Cognitivist: I wasn't really saying that. Oh, wait. I see that you are linking what I've been saying about image schemas with what I said earlier about the formal knowledge that Adam seems to have. So yes, I do agree with how you just summed up what I'm saying, well, at least for this particular case. I don't think it always comes first. And I would be open to different accounts in this case as well.

Phenomenologist: Why are you being so cautious and tentative?

Cognitivist: Well, it's difficult to be confident when one is trying to make sense of the processes driving free-flowing discourse like this. One account might be that Adam's formal knowledge of Newton's laws triggered his enactment of the dance, which, in turn, invoked a mental model and allowed the students to explore the scenario of the two orbiting stars in an embodied way. I would say that there's a good case to be made that Adam is invoking Newton's laws. But it's also possible that Adam had a mental model of rotating objects attracted by a gravitational force already in place. Whether formal knowledge of laws or mental models is driving the reasoning, I expect that there is some interaction between propositional (language-like) and non-propositional (image-like) representations underlying the reasoning we are witnessing in Adam's contributions to the exchange.

Phenomenologist: In other words, you think that in this episode, what we see is a negotiation between formalism and embodied experience? Adam and Beth embody abstract ideas with(in) their bodies and, conversely, they abstract inputs from their bodies into more formal conceptions (Euler et al., 2019).

Cognitivist: That was a nice way of putting it. I believe this episode shows that there is a subtle role that the physics formalism plays in concert with the embodied experience. Adam and Beth need the embodied experience to give meaning to what they are thinking about. Nevertheless, this experience needs to be "tamed," so to speak, by the formalism. Because only some parts of the embodied experience are being given legitimacy by the formalism and other aspects are not. But I would add that a mental model—which is a cognitive structure, not just an "experience"—is probably playing an important role.

Interactionist: Let me jump in here again and play the role it seems I'm particularly suited to play and draw attention to the language you are using. Now you've slipped into talking about "mental models" after introducing the idea of an image schema. Now you owe us a quick explanation of mental models, too!

Cognitivist: Fair enough. OK, let me offer this: I think of a mental model as an analog mental representation of some objects and relations in the world (even on a large interactive whiteboard). The model will be built out of images of objects and their interactions; these images will be interpreted using image schemas. So more than one image schema

can go into constructing a mental model. Mental models that represent physical systems in ways consistent with the laws that scientists have discovered need to behave in ways consistent with those laws. The philosopher and historian of science, Nancy Nersessian (2008), has a lot to say about that.

Interactionist: Thanks, that's interesting. Your description suggests that Adam and Beth's bodies play two roles in their meaning-making process, both as a "role player" and as a "sensor": Adam and Beth are going through loops where they are switching how they use their bodies, both to embody the phenomenon and to use their bodily intuitions (Euler et al., 2019).

Cognitivist: Exactly, and I think that it is a process of activating image schemas that could contribute to the construction of mental models, which provides a link between the body and thought.

Phenomenologist: But at the same time, you continue to make a distinction between body and thought! I can't help but think that your strong focus on cognition positions the body as a kind of objective vehicle (Hardahl, 2019). By foregrounding cognitive processes and the role of the body therein, you lose sight of what it is like for Adam and Beth to *be* in this moment as sensing sentient beings. What about their experiences in the physical environment, pure and simple? Their sense of self and being, their awareness of being judged, and their immersion in the flow of the activity (Toscano & Quay, 2021)? Your take on embodiment is too instrumental.

Cognitivist: Sure, I agree. I am happy to acknowledge that. I do understand the body as an important player in cognitive processes that allow certain reasoning to get done. Experience per se (what you actually consciously feel) is neither here nor there for a cognitivist typically: what's important is to describe what cognitive processes unfold to perform some reasoning task; what people experience or feel is not seen as part of that story; so this is probably where our perspectives diverge, Phenomenologist. Now to take a page out of Interactionist's playbook, I actually think there is some slippage occurring in how different people use the notion of "experience;" it seems to me that phenomenologists use it to refer to conscious feelings, whereas cognitivists interested in the role of the body in thought use it to emphasize the sensorimotor origin of some knowledge structures.

5.2 Interactionist's Scene

Interactionist: Well, you just said you see evidence of image schemas and a preexisting mental model in this episode, Cognitivist, right? From my perspective, I see a physical model of orbiting stars that involves two people dancing together to perform. We can also see changes in the dialogue and in what Adam and Beth do. They articulate and resolve their puzzlement, and a physicist can recognize some canonical phrases in this dialogue, too. Why are you in such a rush to appeal to aspects of knowledge and learning that cannot be observed but must be inferred from patterns in the interaction?

Phenomenologist: I see what you're getting at, Interactionist! Cognitivist keeps referring to something, some constructs, that are not directly accessible to us, right? Some "mental stuff" (Roth, 2013, p. 9) behind Adam and Beth's embodied actions, like mental models, cognitive structures, or knowledge elements. I am reminded of Heidegger, who said, "*A phenomenon is nothing behind which there would be something else. More accurately stated, one cannot ask for something behind the phenomenon at all, since what the phenomenon gives is precisely that something in itself,*" (Heidegger, 1985, p. 86).

Interactionist: Exactly! Besides, Cognitivist, you seem to refer to a lot of things that happened before the episode or hypothetically after. Like what understandings do Adam and Beth have ahead of time, and what do they take away after the lesson? If I understand you correctly, you interpret the dance as a physical manifestation of a mental model Adam has. And I don't want to discount any of that, per se. But I think what my perspective can do really well is understand what we have here in front of us, which is this embodied performance.

Phenomenologist: Oh, I like your focus on what Adam and Beth do as a performance, Interactionist. The performance is neither world nor mind—which makes it so interesting to phenomenologists. Now I am really curious about your take on the episode.

Cognitivist: Me too. Can you give us your analysis of this episode; I'd like to see how far you can go without inferring constructs of unobservables.

Interactionist: Of course. The definition of learning that I always refer back to is changes in participation. So, the learning that's meaningful here with Adam and Beth is bound up in this embodied performance. That in itself is the expression of understanding. And that can be a basis for some kind of formative assessment as well. We don't need to appeal to constructs like concepts and mental models. In fact, reducing this performance to merely image schemas or p-prims would totally miss one of the main affordances of the dance. Namely, that it functions as a single mutually understood act for the students (Euler et al., 2019). The partner dance makes it clear that spinning around always requires two people to pull on each other symmetrically.

Cognitivist: So you're saying there is no need to assume there is something "behind" this dance, like some mental model that is guiding the reasoning?

Interactionist: Yes, pretty much. So, in this sense, my stance is obviously opposed to yours, Cognitivist. I'm interested in how Adam and Beth coordinate and interact with each other and how they understand the physics phenomenon through each other's bodies.

Phenomenologist: So if we didn't have your perspective, we could easily be ignoring the *social* aspects of embodied learning? Is that what you are saying?

Interactionist: Exactly. My tradition emphasizes the sociocultural world of people working together. It's clear to me that social interactions change possibilities for action. It's not just that there is another body and you can do something with the body, but Adam and Beth are actually working together, cooperating to understand the orbital movement of stars. And I think this is something that's part of my idea of embodiment. It goes beyond the mere co-dependence between the mind and the material world. It's about the learning that occurs through embodied coordination of several people interacting with each other. Understanding the role of the body in science education means investigating the social and collaborative embodied mechanisms that drive interactions with science.

Cognitivist: OK, I'm finding this quite abstract, and it's difficult to see what all this actually means in the context of our episode.

Interactionist: Well, we see how gestures (Adam reaching out his hands toward Beth) and bodily positions (Adam and Beth position themselves to rotate around each other) enable Adam and Beth to reason together. The crucial point is that these embodied actions are not externalized translations of individual cognition, but that thinking occurs across multiple embodied minds through gesture and language. I think what we see really well in this episode is how Adam and Beth jointly develop a kind of "fluency" in the use of bodily representations. A semiotician would say that Adam and Beth gain the ability to select and coordinate semiotic resources by recognizing a set of disciplinary-relevant aspects relating to the task at hand (Euler et al., 2019). But no matter how we say it, the crucial thing is that we *see* all of this right in front of our eyes. I think it also gives us insight into how this

particular dance came to be enacted through question and response, dialogue and elaboration, and culturally situated ideas and concepts that are brought into relevance.

Cognitivist: That's all well and good. We certainly are able to see all these things. We see the interactions and the bodily postures. And you're doing as much as you can to articulate the learning experience, getting as much as you can from what you are able to observe. That, I think, is the strength of the social interactionist and semiotic perspectives: there's so much there to be observed if you have the analytical tools to describe and interpret them.

Interactionist: I sense a "but" coming.

Cognitivist: Did you have any doubt? The big question that remains for me is: what are those things going on behind the scenes? Is there something that you don't capture with such a descriptive approach, if you will? Why is Adam quickly bringing into the scenario a model that he enacts physically? After all, he proposes a physical enactment of holding hands and rotating. But, one can ask, well, why? How did he come up with this? How did he think that this would be a good thing to do, to hold hands with Beth and to begin to enact a rotation? So one can ask, how does somebody like Adam construct an embodied concrete model and feel that this is an appropriate and meaningful thing to do for this particular question that they're trying to answer? I still believe there is a very powerful mental model that is constraining Adam in constructing that particular embodied model and leading to logical and causal inferences.

Interactionist: But why care about mental models and cognitive states if you can never have access to them? Why should we try to get into the head of Adam and Beth?

Cognitivist: Well, how far can we come with a fine-grained analysis of what students say and do, including embodied interactions, without inferring cognitive structures? It's not that I'm trying to get into the head of Adam and Beth for its own sake, but I do try to come up with models that best explain their behavior.

Interactionist: But then these are *your* models, the models of a scholar. There is no hope that your models have anything to do with the real performance of Adam and Beth in flesh and blood (Roth, 2013).

Phenomenologist: I am reminded of Hutchins' *Cognition in the Wild* (1995) here; it seems to me that you both would be happy to integrate your accounts; Cognitivist, you can be patient and allow the descriptive analysis to be done first; Interactionist can then hand over and be open to inferences about hidden representations and processes that help make sense of the flow of the interaction. What do you think?

Cognitivist: Yes, I think you're onto something there, Phenomenologist. But let me say that the inside/outside distinction is not really the issue here. A cognitive account of behavior of any kind is a functional description of representations and their manipulation to accomplish a task. Traditional cognitivists believed this all along, but more recently, those advocating embodied and distributed cognition, like Andy Clark (1997) and Hutchins (1995), have made this much more explicit. Hutchins used a cognitive framework that transcended the inside/outside distinction in a very interesting way. He made it clear that we can analyze any system of many parts cognitively (in his case, it was the navigation of a naval vessel). We can then ask, what aspect of the task is carried out by the minds of the people involved, by the social hierarchy of the naval personnel, and the various tools that they use.

Interactionist: OK, but can you get back to your case about mental models?

Cognitivist: Yes, sure. I'll put it succinctly. For me, the mental model is a summary construct that does enable us to predict participation. And, of course, we assume that it is enacted in the brain in some way (or the brain plus public representations like language). Somehow mental models provide us with a kind of predictive power that the language of

participation alone doesn't give you. But let me also add that I'm a bit surprised about your resistance, Interactionist, to postulating entities that aren't seen as part of explanatory models of phenomena. Scientists do this all the time.

Interactionist: But my approach is much more parsimonious, Cognitivist! If I understand you correctly, you're saying that the dance and the gestures, and the spoken words have some counterpart in the heads of Adam and Beth, right? So, according to you, what is made visible in the performance has a corresponding image somewhere in the brain (Roth, 2013). What *I* see is a collective bodily representation of a physical phenomenon that is publicly available to Adam and Beth in the moment. We don't even need to deal with the mental representations to see that we have an embodied performance that gives us insight into the shared meaning-making process happening here. The production itself is the thing to be modeled (Roth, 2013).

Phenomenologist: Wait! Now it's my turn to call you both on your language use. You keep talking about "representations." But I think each of you uses this notion differently. I find this confusing and, I'll be honest, a bit frustrating. From what I understand, you, Interactionist, think about the dance as an embodied representation that Adam and Beth jointly construct and perform to express some shared meaning, right?

Interactionist: Yes.

Phenomenologist: And you, Cognitivist, seem to think about mental representations that reflect and represent knowledge of the world in the brain, and these representations guide the reasoning of Adam and Beth.

Cognitivist: Correct. But I do accept that their language and body movements are functioning as representations that contribute to their reasoning. I accept that representations can be internal (mental) and external (public), and these complement each other; it's not that the internal representation is some equivalent image of the publicly used representation as Interactionist suggests.

Phenomenologist: OK, so clearly, you talk about different things but also partially overlapping. And it's still not clear to me what role the body plays in all of this. What's your take on representations from an embodied perspective, Interactionist?

Interactionist: I'd say that in my tradition, external representations play a key role because understanding, by and large, resides in these representations. For example, Lemke (2004) takes a particularly extreme view; he doesn't even acknowledge the need for internal representations and concepts as mental constructs at all. For him, the concept manifests as a collection of external representations (graphs, equations, spoken/written language, etc.). In this view, understanding science amounts to the ability to coordinate multiple representations of scientific phenomena in meaningful ways.

Cognitivist: Which certainly contrasts starkly with the typical cognitivist view of concepts as mental structures.

Phenomenologist: I see. Interactionist, can you explain this in the context of our episode? What role do the body and bodily representations play for Adam and Beth?

Interactionist: Sure. I think this episode shows us that Adam and Beth's bodies can function as improvised representations of a physical phenomenon. The students use their bodies to enact a dance as a metaphor or an analog to a binary star system (Euler et al., 2019). And this representation is improvised in the sense that it begins with embodied actions in everyday use and then transitions to a more disciplinary and scientific practice (Steier et al., 2019). And Adam and Beth can explore metaphorical parallels between their bodies and the entities they represent because they use their bodies as representations of physical entities (Euler et al., 2019).

Phenomenologist: Nice!

Interactionist: So, if we return to our definition of learning as participation, being able to construct, perform, and work with these improvised representations is potentially a form of transfer that Cognitivist was talking about earlier when he asked what students take with them after the episode.

Cognitivist: Oh, that's an interesting take on transfer, Interactionist. Not quite what I had in mind, but I like it!

Phenomenologist: Me too. You're saying that the learning process consists in building this bodily representation, right? And Adam and Beth take with them the ability to work together and construct representations with their bodies and the material objects around them, which they use to express some kind of shared understanding. Nice. So, Cognitivist, what do you mean when you talk about representations?

Cognitivist: Well, at the heart of the traditional view in cognitive science is the idea that knowledge is represented as relationships between mental symbols. And then there are those mental representations, which we call concepts, that have meaning by virtue of referring to entities or situations in the world and by virtue of their inferential roles, that is, the role the symbol plays in a network of other symbols.

Phenomenologist: This sounds very different from what Interactionist just said. And I don't really see how the body plays into your tradition. If I understand you correctly, then representations are the disembodied mechanism by which our brains get information from the world. Our access to the world is mediated and enabled by mental representations. Is this what you're saying, Cognitivist?

Cognitivist: Well, yes and no. Traditionally, the cognitive sciences and the so-called "representational theory of mind" did conceive of cognition as entirely about symbol manipulation, which presumably happens in the brain in some way (Hutto & McGivern, 2015). But I want to say that there are subtleties here that are underappreciated in these discussions. For example, if I asked a cognitivist like Jerry Fodor (1975)—sadly, he has passed away, so I can only consult his writings—how a symbol in the mind "means something," he would argue that its meaning comes to a large extent from the causal processes outside the head that lead to the symbol getting triggered in the mind—i.e., my symbol for gold means gold by virtue of being triggered by all those things in the world that are gold, and that might involve using tools to determine that or ask an expert to confirm, etc. This is the so-called "causal theory of reference." So you see, the critique that cognitivists are only concerned with what is "in the head" reflects a misunderstanding.

Phenomenologist: I see; thanks for clarifying this.

Cognitivist: Reasoning, though, in the traditional cognitivist view, is a purely mental process. But while it is "mental", there are embodied accounts of mental representations that accept that many of these emerge from sensorimotor interaction with the world. Piaget had a similar view in his account of how concepts emerged from sensorimotor experience. So the body's interaction with the world is the source of powerful mental structures that participate in reasoning. We talked about image schemas earlier; these are mental representations, but they have bodily (both perceptual and motor) interactions in the world as their source. I could also add that more recent "embodied cognition" theorists are happy to acknowledge (indeed insist) on the role of the body in shaping mental representations; indeed, they would say that perception is *for* action and is not some objective process of "registering" what's out there.

Phenomenologist: Such a relational account aligns more with the phenomenological perspective that everything we experience involves both the inner and the outer. By and large, phenomenologists reject the traditional view of mental representations arising in consciousness – or at least, this view would court much skepticism (Zahavi, 2019).

Cognitivist: Right. I don't think we should privilege representations and processes internal to the mind. I believe that abstract conceptualization and reasoning are grounded in sensorimotor experiences and rely on material and symbolic artifacts. Sometimes the body itself – e.g., actions (including symbolic gestures) and positioning in space – can play a role in cognition. This is why I actually like to describe cognitive processes as "distributed" across the inside and outside of the body. I'm very comfortable with that idea.

5.3 Phenomenologist's Scene

Phenomenologist: So far, I am impressed by your attempts to describe and explain the learning processes that we observe in this episode, Cognitivist and Interactionist. And I've learned a lot from your descriptions already. But all of this is so functional, so instrumental in nature! Both of you appear to lose sight of the whole person, of Adam and Beth's lived and felt experiences. It's this lived experience that should be the starting and endpoint of phenomenological research (Van Manen, 2016).

Cognitivist: Can you explain this a bit better, Phenomenologist? What do you mean by the lived experience? This sounds vague and doesn't tell me much about the learning in this episode!

Phenomenologist: Sure, Cognitivist. Lived experiences are everyday experiences as they come into being—situated and immediate, pre-reflexively taken for granted as reality and not as something that is perceived or represented (Merleau-Ponty, 1962).

Cognitivist: That is a mouthful. "Pre-reflexively taken for granted …" I find it hard to engage meaningfully with this kind of discourse.

Phenomenologist: Patience Cognitivist. We all have our technical language. Let me finish; maybe then things will start to make sense.

Cognitivist: By all means; sorry for the interruption. But I do get worked up about these things. Please, continue.

Phenomenologist: OK, so as I was about to say, I believe that if we really want to understand the learning in this episode, then we need to understand how the binary star system, Newton's laws, and, not least, the dance appear as what they are and with the meaning they have for Adam and Beth. As a phenomenologist, I am interested in the givenness of these physical phenomena, mathematical models, and cultural products (Zahavi, 2019).

Cognitivist: Hm, but …

Phenomenologist: Hold on; don't interrupt again. To understand how these things are "given" to Adam and Beth, we need to focus on the two students and on their subjective accomplishment that is at play in order for the dance to appear as a model of binary stars. The physics learning we see in this episode, and really any understanding of the world, is always perspectival. This is why phenomenological analyses are characterized by their attention to the co-constitution of self and world, to "being-in-the-world.".[4]

Interactionist: So you're suggesting we first consider how Adam and Beth perceive the task? And then present the activity from their perspectives?

Phenomenologist: Yes, and how can we look for the students' subjective and lived experiences in this episode? Ideally, we would have interviewed Adam and Beth

[4] Heidegger (1962) used hyphens to illustrate this special correlational character of "being-in-the-world" to illustrate the conceptual disintegration of the dichotomy between mind and world (Popova & Rączaszek-Leonardi, 2020).

because interviews usually serve as the source of knowledge in phenomenological investigations (Alhazmi & Kaufmann, 2022). But even without interviews, we can say a fair bit about what it was like to engage in the dance. First of all, Adam and Beth must have become aware of the dance by being aware of their own bodies and how to interact in this situation. This means that their perception of the dance was interwoven with self-awareness—a bodily experienced selfhood, if you like. Second, there is the aspect of intersubjectivity: the dance existed for both of them and was experienced as such. This exploration was also temporally extended because the dance involved a series of actions (Adam reaching his hands out to Beth, the two holding hands and positioning themselves, etc.), and the materiality of the interactive whiteboard, the chair, and the surroundings served as the horizon of Adam and Beth's experiences in this setting.

Interactionist: So, you suggest we consider Adam and Beth as embodied and participating subjects in this episode, right? And look at the temporal unfolding of their embodied actions? This sounds like what I would try to do in my analysis as well. After all, I also focus on the material and sociocultural affordances in this episode.

Phenomenologist: Well, that's true. And I really like your use of "affordance" there; after all, affordances are relational at heart, and that is key for me: they unify the knower and the known (Popova & Rączaszek-Leonardi, 2020). Nevertheless, the body plays mainly a functional role in your description of learning processes, right, Interactionist?

Interactionist: I suppose so. Go on.

Phenomenologist: Your embodiment of action does not refer to the *felt experiences* of Adam and Beth's bodies while they are (inter)acting in this room. For example, I would draw attention to how the two don't actually complete the dance. They only invoke it partially by holding hands and leaning outward, and from then on, it becomes a thought experiment. And it makes me think, would the full spinning dance put them into a wild movement? And if so, would they have completed it if they had had the space? Or does the classroom, which is characterized by routines and habits embedded in the body (Hardahl, 2019), not recognize and condone wild movement? In other words, how do Adam and Beth *know* the space they are situated in?

Interactionist: Even though I find the idea of felt experiences and the lifeworld of a student interesting, I am always skeptical of referring to constructs of hidden entities that I cannot observe. This is similar to my concern with the cognitivists' tendency to do the same thing with mental constructs. But can you explain to me why *you* find appealing to the inner world of the person so useful?

Phenomenologist: Sure. Adam and Beth inhabit and know the classroom through the desires, goals, or necessities they feel in this space, which are realized through bodily engagement (Merleau-Ponty, 1962). The classroom, as such, is not a container for objects of experience (the interactive whiteboard, chairs, or table) but rather an "organic relation" based on embodiment (Thøgersen, 2004, p. 131). This means that the classroom gains meaning as a classroom because it provides Beth and Adam with a place where they can perform certain actions (project images onto the interactive whiteboard and write on it, sit on a chair, engage in discussions about science, and so forth). It is all of these possible actions that extend this space as a *human space*, where actions are guided by the desires, goals, or necessities *felt* by Beth and Adam in that particular moment. Their dance is thus movement situated in a particular context and driven by subjective desires, and from my perspective, knowledge about how Beth and Adam understand the context and their desires for moving in this way is central to making sense of what we see in the episode.

Cognitivist: I think I get your point. We don't factor in the felt quality of what it means for Adam and Beth to engage in this dance and in this classroom space in particular. Our explanations of the learning activity lacked this subjective dimension.

Phenomenologist: Yes, Cognitivist. From my perspective, we need to focus more on students' everyday experiences and less on scholarly models of how students learn. Lifeworlds transcend scientific knowledge (Van Manen, 2016), as scientific knowledge is one way, not the way, to understand human lifeworlds. This means that abstract scientific knowledge must be connected to being and acting in the world as the basis for genuine understanding (Østergaard et al., 2008).

Cognitivist: Phenomenologist, you raise interesting points here. And I can see that there is value in acknowledging students' experiences and first-person points of view. Maybe we'd produce better explanations if we allowed for felt experience as a crucial dynamical element in our models (Popova & Rączaszek-Leonardi, 2020). But—setting aside the somewhat inaccessible discourse (to me, at least)—there's still one issue that bothers me about the phenomenological approach.

Phenomenologist: Yes?

Cognitivist: If you study the details of Adam and Beth's experiences, who they are, how they feel, etc. You sound like you are really trying to avoid generalizations as much as possible. But presumably, we're looking at this particular episode so that we can ultimately learn something about designing learning environments for others too. I think there's inevitably an inherent generalization that is being made there. And I'm very comfortable with that. After all, when we observe processes involving individuals, they always resemble one another in some way. And this is the case when we observe people involved in learning situations. They're not always different. That's important to recognize, especially when analyzing learning, because if we take an extreme position that each episode is always highly situated and exceedingly specific, then I don't see the rationale for doing this kind of analysis in an educational setting since we're actually always implying that we're learning something that's generalizable to a degree.

Phenomenologist: I am not surprised that you bring up this issue, Cognitivist. Having just discussed the relevance of subjective perspectives and lived experience, I can see there is an apparent tension between our traditions. From what I understand, the cognitive lens is driven by the desire to say something about people in general, students in general, learning in general, or at least learning science in general. And I can see the value of drawing on mental models and other mentalist abstractions as a route to generalization.

Cognitivist: Right.

Phenomenologist: Phenomenologists seek to avoid the reduction of the complex, broad relations between learners and their environment that goes hand in hand with the attempt to say something about people and their brains in general. This kind of reduction wouldn't do justice to individuals, phenomena, or their mutual relations (Østergaard et al., 2008). Nevertheless, I believe that the phenomenological enterprise is, in a sense, also broader and more general than cognitivism because we think of learners not just as brains with bodies but as persons with an identity, a sense of purpose, confidence, preferences, etc. By honing our ability to empathize with individuals, we don't lose sight of students' lifeworlds; it is in these lifeworlds that science learning takes place. How can studying the brain, image schemas, or mental models ever tell you something about lifewords?

Cognitivist: Well, in a sense, that might be true. But surely, the brain plays a particularly important role in storing and manipulating information. And people's brains are certainly similar enough that generalizations seem appropriate. I would argue that the activities we see in this episode are constrained by general features of the human brain

as applied to this situation: how people map knowledge from one domain to another analogically, how they form mental models to make sense and reason about things they observe; and also how linguistic and other meaning-making resources (to use Interactionist's terminology) are generated and interpreted. I take an interest in universal patterns of students' conceptual understanding of natural phenomena and scientific theories. What patterns can be generalized across people? This is what motivates me.

Phenomenologist: But Cognitivist, each person is different, and each body is different. If Husserl and Merleau-Ponty are right that the body is the sole vehicle for having a world (Popova & Rączaszek-Leonardi, 2020), then everybody's experiences of the world must vary. I like how Sherry B. Shapiro characterizes this. She writes that there is "no Archimedean viewpoint; rather, knowledge is always situated and constructed in a dialectical relationship between the individual and the culture in which she/he lives" (Shapiro, 1994, p. 61). It is a relationship that is inscribed in and on the body as a lived process and forms the basis on which we understand the world. This is why I have a hard time looking at the body as a kind of generic mass, a view from nowhere, essentially. To me, the body is a matter of looking at SOMEbody.

Interactionist: I hadn't thought about it that way, Phenomenologist. That's a fascinating perspective.

Phenomenologist: Thanks! Let's adopt my perspective to look at the sensation of being pulled out while spinning around. Of course, spinning involves several sensory inputs (haptic, proprioception, sense of balance, etc.), so this is a very embodied and directly-felt experience for Adam and Beth.

Cognitivist: Oh, you're thinking of the moment when Beth shows resistance to the idea that the forces in the orbital system are pointing inwards as opposed to outwards?

Phenomenologist: Exactly. Beth says, "*Here, they are directed away from each other"* (frame 20).

Cognitivist: Which is a common idea that many physics students express.

Phenomenologist: Right! Beth is SOMEbody, and therefore, it just feels natural for her to trust her body: if she feels she's being pulled outwards, she concludes there's a force pulling her. So from the discipline's perspective, there's some danger to felt embodiment; there's a danger to simply trusting your senses and your first-person point of view. Her immediate and situated encounter with the phenomenon does not directly lend itself to disciplinary ways of knowing (Airey & Linder, 2009). There's a sort of mismatch between the outward (centrifugal) pseudo-force that Beth feels when she spins and the inward (centripetal) force that is responsible for the circular motion.

Interactionist: You need to detach yourself from your experience to a degree to adopt a physics disciplinary discourse.

Phenomenologist: Exactly! You may wonder if Beth's felt bodily experience during the dance is legitimate. From a physics perspective, she has to start distrusting her body, doesn't she? We cannot place ourselves out of our own bodies. We are always in the reference frame of our body, and if this reference frame is accelerated, we will always experience pseudo-forces that feel like real forces to us.

Cognitivist: Right, it's really hard to step out. I'd say it's impossible. So you need to transcend your senses, in a sense, to really appreciate why a centrifugal force is not really a force. To understand the physics of rotating bodies. So I very much agree with you that Beth's initial assumption is embodied. Using my terminology, I'd characterize this in terms of the activation of a knowledge structure like a p-prim or image schema that grounds compelling intuitions.

Interactionist: This is interesting. We all think that this moment is an important one from an embodiment perspective. But we all draw on different notions of embodiment[5] to explain the relevance of this scene. And there is a difference in whether or not we resort to hidden constructs and the inner word of learners or if we just look at what is publicly observable to us.

Phenomenologist: Huh, tell us more.

Interactionist: Cognitivist, you talk about image schemas, so your take on embodiment is through a sensorimotor account of conception and inference. Phenomenologist, you talk about the felt experience of being pulled out while spinning, so your take on embodiment is a phenomenological account of bodily consciousness. Both image schemas and the students' felt and subjective experiences remain hidden from our view and are, in fact, constructs you introduce to theorize about what's going on in the episode. I, on the other hand, highlight the publicly available affordances that come with the embodied coordination of Adam and Beth's dance, so my take on embodiment is a sociocultural one emphasizing the body as mediating communication.

Phenomenologist: What if the disagreement between our traditions is partly the result of different understandings of the role of the body in science learning?

Interactionist: I get the sense that our traditions aren't as different as they seem, especially if we arrive at similar conclusions when looking at an episode like this. It's just our starting points and the way we reach our conclusions that seem to differ.

Cognitivist: Well, speaking of starting points and conclusions. I still don't see how we can properly analyze this episode and draw conclusions about learning using a phenomenologist's methods. Phenomenology sheds light on the background condition of students' experiences, so to speak. But it doesn't tell us much about learning or educational practices more generally, does it?

Phenomenologist: Sure, you are partly right, Cognitivist. Phenomenology is more of an existential perspective. It doesn't offer a theory of learning directly. But it does provide a coherent theoretical background for considering the necessary conditions for experiencing the world. I think that one of the strengths of the phenomenological method is that it gives us insight into students' motivations and actions; it illuminates their experiences and perceptions in the science classroom. Giving voice to these experiences can challenge structural or normative assumptions of what it means to "do science" in the classroom. But, of course, this requires interview data or immersive ethnographic data where the researcher gains such emic perspectives (Hardahl, 2019). I myself have been frustrated that a phenomenologist's methods often lack the tools needed to unpack a learner's experience as it unfolds in a specific context of science learning in action. A way forward is, however, to partner with other theories and methodologies, such as pragmatism (Hardahl et al., 2019) or embodied cognitivists, such as Lakoff and Johnson (Knudsen, 2009).

Interactionist: I'm glad you're saying this, Phenomenologist. I had a similar hunch about phenomenology, and I believe that our traditions could complement each other well. After all, both of us agree that students' embodied engagements create mechanisms for learning, reasoning, imagination, and abstraction.

Phenomenologist: Right. The interactionist and cognitivist traditions may offer better tools to analyze the role of embodiment in science learning. And I think we can frame that

[5] The physical sense of embodiment focuses on image schemas, the phenomenological sense on lived experience, the ecological sense on bodily enactment, and the interactionist sense on joint production (Kersting et al., 2021).

as a positive thing, too. If one tradition stops where the other begins, this could be where productive research takes place.

Interactionist: Exactly! If we push for better awareness of how we understand the role of the body in science education in our traditions, if we better understand each tradition's conceptual core, we can work towards mutual enrichment. Maybe our different traditions can contribute to a larger programmatic whole.

6 Act IV

In which the personas realize they share some theoretical and methodological commitments but ultimately try to answer different questions, leading them in different research directions in their search for answers.

Phenomenologist: This conversation is fun! And I can see there is value in our conversation when we step outside the boundaries of our traditions. I believe that we have an understanding of embodiment in science education that transcends our respective traditions. We make intuitive sense of these ideas, yet when we write about our research, we get quickly into the jargon—and the misunderstandings begin.

Interactionist: I agree. It's so easy to confuse our analytical constructs and our conceptual vocabulary for ontological reality. Maybe if we better understand our core assumptions, we can refine and even unify our terminology to describe embodied science learning. To me, it seems that our traditions have developed more or less independently of one another but nevertheless have converged on a set of key tenets that acknowledge the role of the body and embodiment in cognitive tasks in science education.

Phenomenologist: Yes, clearly, we have a shared domain of scientific interest, but our traditions have approached this domain from different avenues, which has led us to separate research trajectories. Our conversation has made me appreciate the parallels and resonances between our approaches despite obvious differences in our analytical foci and methodological tools.

Cognitivist: Yes, I often feel that there really is no difference between all of these traditions in a fundamental sense. At the end of the day, there is a body with neurons and flesh and blood, and it does stuff. And you can look at it from a very physical point of view. And then there are symbol systems that people use that you can see on paper and on boards, and on diagrams and whatever. And all of this is stuff that can be observed. And there's flow; there's change. These acting creatures with bodies and brains and symbol systems evolve and transform and look different at different times and produce different symbols and actions, and, of course, actions that are treated as symbols, like the dance we've been discussing.

Interactionist: I like the approach you're taking here. Don't think I haven't noticed that you're trying hard to avoid any of the terminology associated with any of our traditions.

Cognitivist: Yes, that's exactly what I'm trying to do. Where I was heading with this line of thought was to say that at the end of the day, we're all somehow offering models of these acting agents and changing agents in the world, but our models look different. So what cognitivists seem to simply be saying is that there's some specific aspect of this that the brain is doing. And we don't know exactly how the brain does it (yet, we're working on it), but this is a kind of a summary statement of what it's doing. I don't know why that would be so fundamentally different from doing an interactional or discourse analysis and distilling the specifics of a dialogue into a summary account of meaning-making, capturing the

changes and moves of different participants in the language of the researcher using their own analytical framework. I don't see them as necessarily fundamentally different because, presumably, everybody believes that the brain is an important organ and that without it, a lot wouldn't happen. And that it must be that the brain is doing something that the legs and the arms are not doing. It seems to me that we are all modeling different aspects of a whole.

Interactionist: I think it's quite satisfying to take this big-picture perspective. If we're zooming that far out to say: we have bodies, we have brains, we're acting in the world. I think then it is easy to agree that embodiment plays a crucial role in science education. Then it is easy to identify common strengths of embodied approaches to science education research – rather than getting caught up in differences between our traditions. But I think we have seen that there are some quite fundamental differences in our perspectives when we zoom in a little bit which shapes the framing of the questions we're asking. And we shouldn't gloss over these differences because they become relevant if we think about what we want to achieve with our different levels and timescales of analyses. At the end of the day, to qualify as good educational research, our analytical tools need to be up for the task of studying science learning, and they need to provide valuable insights into what it means to learn science.

Cognitivist: I agree. Implicitly we're trying to answer different questions by looking at the same situation of Adam and Beth trying to understand orbital motion. And that can generate some friction between our perspectives. It's not that we offer different answers to the same questions, but actually ask different questions in the first place!

Interactionist: But this motivates me! How remarkable it is that three people can care about the same data set in such a basically similar way; we're all interested in what is happening to the learning and the conversation about physics here. And yet, our approaches are so different. The fact that we can be so aligned in terms of what we really care about in the learning and yet still our understandings of this episode and what we pay attention to are so different. I think that's remarkable.

Phenomenologist: Indeed, it is. This leads me to think that we should be able to highlight the connectivity between our traditions more than the separation. Wouldn't it be fun to try to identify the scope of each of our traditions for what I would call "mutual enrichment"? What I mean is, we can ask: what is the usefulness of our different approaches? What do our perspectives best contribute to our shared endeavor to improve science education practices?

Cognitivist: I get the impression that we can work together productively, yes. Each of us can contribute with our own unique perspectives, knowledge, and methods, and we can leverage the strengths of our respective traditions.

Interactionist: Nice! This is such a productive way for us to move forward. It's not about one tradition being better than the other but about sharpening our arguments, clarifying our jargon, and highlighting the diversity and, when possible, the complementarity of our viewpoints on and methodological approaches to embodiment in science education.

7 Act V

In which we, as authors, reflect on the conversation and how it has reshaped the three personas and our understanding of embodied science learning.

In this section, we return to the initial questions that opened Act I and distill the lessons learned from this dialogue. Dialogue, especially when interlocutors listen to each other, can lead to better mutual understanding. The negotiation of meaning inevitably leads to greater convergence, certainly in improving an interlocutor's understanding of the other, but potentially in interlocutors' actual viewpoints. The dialogue we have presented between an interactionist, cognitivist, and phenomenologist helped sharpen how we view each position enabling us to articulate better convergence among perspectives, how they might complement each other, and what points of fundamental differences in perspective must be acknowledged.

One important outcome of our dialogue was that it enabled us to articulate more explicitly dimensions along which convergences, complementarities, and fundamental differences can be expressed. All three perspectives make assumptions and raise questions about the body: the body as a basis for thinking, living, and experiencing; the body as an active agent; and the body as socially situated and in interaction with others (Kersting et al., 2021; McGann et al., 2020). Here, we see broad areas of resonance and possible convergence between the traditions. However, it became clear that we needed to be more explicit about the driving questions that each tradition tries to answer and what data and unit of analysis each tradition needs to answer these questions. The dialogue also made it clear that different epistemological assumptions and goals lay behind each tradition's driving questions. Consequently, the personas diverged in what each considered satisfying answers. Traditions also differed with respect to their agenda being primarily descriptive or explanatory and their willingness to engage in inferences about the unobservable; with respect to the goal of generalization or attention to the particulars of individuals and contexts; with respect to the kind of theory of learning sought, and indeed, *whether* a theory of learning was sought; and with respect to the relationship between the perspective (one might say, "subjectivity") of the researcher/analyst and that of the learners being analyzed.

Being explicit about these dimensions has helped us sharpen our characterization of the different traditions in regard to embodiment and the extent to which they converge, complement one another, or differ more profoundly. It has also helped us fine-tune our understanding of the theoretical constructs, recognize the overlap between ideas despite different terminology, and recognize how meanings differ when the same terms are used. Crucially, the explicit articulation of these dimensions helps us formulate more precisely how each tradition views the role of the body in science education. We believe that research on embodiment in science education will be more cumulative and productive if our community can recognize that different traditions have recognized the central role played by the active body in interaction with its material and sociocultural world.

Our Interactionist entered the conversation driven by the questions: how did the dance emerge as a shared representation? How did Adam and Beth select this representation and coordinate it with other resources for meaning-making? And what affordances did the bodily interaction between the students provide? To find answers, the Interactionist was keen to describe the wide range of semiotic resources that Adam and Beth drew on while they jointly worked on the simulation of the binary star system. Throughout the dialogue, examples of such resources were the dynamic simulation visually represented on the whiteboard, the language that the students read off the whiteboard and produced themselves, the gestures that they used to point to aspects of the simulation and trace some of the stars' movements, and their bodies when they enacted a dance that they treated as representing the binary star system. But the Interactionist is not primarily interested in just cataloging these semiotic resources, and certainly not in identifying what each individual learner is saying or doing to infer their "conceptual understanding." Rather, the unit of analysis is the pair

of learners engaging in a meaningful interaction. The goal is to describe the interactional *sequence* in semiotic terms and understand *how* exactly Beth and Adam *make* meanings, for these meanings are not seen as residing in the students' minds conventionally associated with their words, gestures, and body movements, ready to be drawn on when needed to communicate an "idea." Instead, the meanings *emerge* in the interaction. Beth and Adam hold hands and enact a little dance as they try to make sense of the binary star system; the dance emerges as a model of the binary star system; it is a model *performed* by their bodies and publicly available to them. One might say the dance "represents" the system Beth and Adam are discussing, and enacting it reflects their "understanding." Although an interactionist might use words such as "representation," "understanding," or "meaning," we need to be careful not to allow cognitivist assumptions to creep into our interpretation of the Interactionist's agenda. This agenda is primarily descriptive, and the Interactionist does *not* speculate about the learners' minds or try to infer constructs of unobservables.

While the focus of the Interactionist is on *this* interaction involving Beth and Adam, the richness of the semiotic resources, and the novel meanings that emerge in their use, generalization is a feature of the interactionist agenda. There is a search for pattern: patterns of the kinds of entities that contribute to meaning-making (language, learners' bodies, material artifacts); patterns in the interactions that unfold (different viewpoints and positions initially adopted by the participants gradually giving way to agreement, and the adoption of shared perspectives); and also patterns across interactional episodes (observing Beth and Adam in a different, but similar, situation might reveal similar performances, including the use of language, gestures and their bodies, and meanings that emerged before might be retrieved and put to new use, but this time more fluently and efficiently). For the Interactionist, accounts of learning crystalize through multiple analyses of interactions: each analysis is an analysis of the here and now of meaning-making, but when higher-level analyses look across interactions and patterns, variation can be discerned, and learners' changing participation can be characterized across settings. Indeed, the Interactionist understands learning as changing patterns of participation and increasing fluency in the use of disciplinary semiotic resources (e.g., Lave, 1991).

Educational insights can be achieved by describing how instructional materials and activities *afford* the construction and maintenance of productive meaning-making; what is viewed as productive by the educator is that kind of meaning-making that resembles those of the relevant disciplinary community of practice (in the case of Beth and Adam, this would be the community of physicists). The body emerges from this interactionist perspective as a powerful semiotic resource (both in the use of gestures and the whole body) that can be added alongside language, visual/diagrammatic, and mathematical representations, thereby opening up new possibilities for coordinated meaning-making and, therefore, learning. Yet it is again important to note that the body is not a tool of the mind but rather seen as a resource of the activity itself. The Interactionist's account of meaning-making will respect the perspective of the learners since the goal is to identify the meanings that these learners make in and through their interactions. Nevertheless, the outcome of the analysis, if presented to the learners themselves, may seem alien to them. Not all meaningful acts are conscious ones; for example, many do not realize how much they gesture when they speak and how much the success of their thinking and communication relies on these common behaviors that often pass unnoticed by those who produce them.

The Cognitivist entered this dialogue with a set of different questions: what knowledge structures do Beth and Adam possess, and how do these structures guide their decision to engage in the dance? What cognitive processes are unfolding in the minds of each individual as they participate in the dance, and how do they use public representations to extend

the reach and power of their mental representations? Throughout the dialogue, the Cognitivist took an interest in states of knowledge and processes of change that impact those states of knowledge. While the Cognitivist clearly shares the Interactionist's interest in the interaction as a process and the meaning-making that unfolds, describing that meaning-making is not an end in itself. Besides, the Cognitivist is concerned that the interactionist approach is in danger of ignoring the individual during social interactions. To the Cognitivist, Beth and Adam's interaction serves two different functions. First, it is the tip of an interesting cognitive "iceberg": words, gestures, and body movements, when scrutinized, constitute a window onto an invisible mental life that lies behind and is seen as explaining the meaning-making observed. Second, the interaction is seen as causally impacting this mental life and the changes that occur within. So, the interaction both provides evidence to infer about cognitive states and processes and is part of the mechanism that changes these states and processes. The Cognitivist agrees with the Interactionist that the moment in which Beth and Adam hold hands and enact a dance is a significant moment worthy of description and analysis; the Cognitivist also agrees that locating that moment in a sequential interaction is important—what came before and what comes after helps us understand the moment itself, what leads to it, and what it contributes to what happens afterward. To the Cognitivist, however, Beth and Adam's different roles and their evolving contributions to the interaction are a basis for inferences into their knowledge states: the concepts and laws they might already understand, the models they might draw on or construct, and the processes that might explain how the dance changes the way the students understand binary star systems.

The Cognitivist draws from prior generalized cognitive models concerning students' lay conceptions, common everyday intuitions, partially (or well) understood physical laws and principles encountered in school, and assumptions about different formats in which knowledge has been shown to be represented. From the *embodied* cognitivist perspective, Beth and Adam are assumed (like all human beings who have interacted with the material world around them) to possess certain knowledge structures and cognitive capacities that are grounded in sensorimotor experiences—such as "image schemas" (like *forced motion* and *linked circular motion*), imagistic simulation, and mental models. The Cognitivist uses elements of the language, gestures, and bodily movement that Beth and Adam produce to suggest that they are activating certain cognitive structures and capacities (which prior research has documented), using these to interpret each other's words, gestures, and bodily movements and the visual representation of the binary star system on the whiteboard. Like the Interactionist, the Cognitivist is interested in what emerges in the interaction; the Cognitivist is interested in knowledge *change* after all, and as an embodied cognitivist, grants that knowledge is not simply something that is "in the mind" but is distributed over internal (mental) structures and processes and external objects and symbolic systems.

But herein, we see the tension between the Cognitivist and the Interactionist. The Interactionist, who might, in principle, see some role for mental constructs, sees the Cognitivist as too quick to infer the existence of that which cannot be seen—thereby also running the risk of partly neglecting the social aspects of the learning. After all, the Interactionist defines learning as changes in students' participation: the point is not that embodied actions are externalized translations of individual cognition, but that thinking develops in the interaction between students (Kersting et al., 2021). For the Interactionist, the learning processes that unfold during the interaction are more interesting than the pre- and post-states of knowledge. On the other hand, the Cognitivist, in focusing on the learning of *individuals* and what they might take with them (or "transfer") from interactions such as Beth and Adam's to other situations, feels the need to speculate about mental structures and

transformations. Knowledge about such mental structures could predict what the two students (and others like them) are (would be) likely to be able to do beyond this interaction. Although the Cognitivist acknowledges the potential value of describing the orchestration of speech, gestures, and bodily engagement in much detail, there remains the important task of "explaining or making predictions about how exactly these resources are 'spontaneously' deployed for the enactment of cognitive functions" (Núñez, 2012, p. 329). The role of the body to the Cognitivist is that it is the source of certain kinds of mental representations and capacities that support understanding and reasoning. As an analyst seeking generalizable cognitive models that explain observed meaning-making, the Cognitivist is comfortable positing (often unconscious) knowledge structures and processes that would seem very strange to the learner presumed to possess them. Many constructs—such as "image schema," "p-prim," "mental model," and even "concept"—need a careful definition because they do not have counterparts in the everyday language of the learner who is the object of analysis. In that sense, and similar to the Interactionist's approach, the perspectives of the researcher and learner remain distinct from one another.

The Phenomenologist asks yet another set of questions: how do Adam and Beth's actions tell us something about who they are and how they come to know and learn about science? What kind of habits and repertoires of action do the two students associate with the situation? And how are their actions expressions of knowing? While the Interactionist and Cognitivist are eager to unpack the meanings or interpretations that learners are making, they adopt an analytical stance of subject/analyst to object/learner. And although there are certainly differences in their objectifying the learner, the Interactionist and Cognitivist differ markedly from the Phenomenologist, who rejects such dividing dichotomies in the first place. The Phenomenologist argues that perceptual experiences present learners with the object directly and immediately; thus, there is no need to divide the subject from the object. And neither is there the need to assume that "objects need to be internally reproduced or represented in order to be experienced" (Zahavi, 2019, p. 22). The task of the Phenomenologist is to enter into the lifeworld, the lived and felt experience of the learner in the particular learning setting. From this perspective, Beth and Adam are not simply "meaning makers using semiotic tools to make sense of a physics problem" or treated as "bodies that happen to be vehicles for cognitive structures and processes." They are whole persons with a history who find themselves here in this place. Throughout the dialogue, the Phenomenologist repeatedly guided our attention to what Adam and Beth make of the situation—and of each other. Adam takes Beth's hand and enacts a dance as they work on the physics problem. In analyzing this moment, the Phenomenologist would like to enter into the lived experience of each at the moment. How do the students' actions tell us something about who they are and how they come to learn science? In contrast, a cognitivist might ask: why does their experience matter? Whatever is impacting their talking and acting can be inferred on careful analysis; what they experience or feel is irrelevant. An interactionist might say: whatever meanings are relevant will be apparent in our analysis of the meaning-making emerging in the interaction.

It might seem as if these three approaches are different routes to the same outcome, but the Phenomenologists' perspective is both narrower and broader than the Cognitivist and Interactionist perspectives. The Phenomenologist is interested in the particulars: this person, here, now, in this place. Let's take Beth as a case in point; if she was to be interviewed after this problem-solving session involving the dance, what would we learn about her experience: what did she feel when she walked into the room? How did she experience it (a cold, bland classroom with hard chairs; or a modern, well-equipped classroom with versatile seating)? How did she feel about Adam taking her hand and enacting a little

dance (was he seen as a warm, relaxed colleague/friend creatively and amusingly engaging in an academic task, or as a forward man, taking liberties as he pushes through with his own problem-solving agenda)? An interview might reveal, narrowly, such particulars of Beth's experience. At the same time, the Phenomenologist is simultaneously inviting a broader perspective on this interactional episode than either the Cognitivist or Interactionist. This line of analysis might reveal many aspects about Beth as a person experiencing the episode: her identity and her sense of purpose as a physics student; the extent of her confidence in herself as someone who does not know something right here, right now, in this setting; the gendered nature of her experience and the gendered nature of her perception of Adam's behavior. We could go on! It is expected that this epistemological (or maybe one should say "existential") orientation would resort to a certain theoretical language to characterize the target of the analysis: "lifeworld," "experience" (as "lived" or "felt"), and "worldview". It also makes sense that there is an insistence on the "relational" nature of experience and the need to dissolve the subject/object dichotomy (the room that Beth is in is different from the room that Adam is in since they might experience it differently; the enacted dance is not one single act, since both students participate in it and each might experience it differently). Finally, one might ask: what does all this have to do with learning? As the Phenomenologist said during the conversation: the goal is not a theory of learning. But this approach seems to be all about learning; it is about building an account of the experience of learners in a learning setting. But careful: that either Beth or Adam experience themselves as learners, what they are doing as learning and where they are in a learning setting is itself something the Phenomenologist's analysis must determine. In contrast to the Cognitivist and the Interactionist, whose perspectives as analysts remain distinct from those they analyze, the Phenomenologist tries deliberately to enter the world of the participants and aims to view the scene from their participant's point of view.

8 Conclusion and Implications

Despite growing recognition of the role of the body and, more generally, the embodied and material aspects of learning to our understanding of science education, this recognition has taken many different forms across different research traditions. For that reason, considerable theoretical and methodological differences remain and hamper productive discourse in our community. This paper critically examines such differences and articulates the relationship between the body, embodiment, and science learning by bringing the cognitive, social-interactionist, and phenomenological research traditions into dialogue. The originality and value of our contribution thus lie in bringing together three distinct research traditions and carefully analyzing the role of the body in science education within and across these traditions. Methodologically, we have engaged in a year-long series of conversations and role-playing between the authors, which we recorded, transcribed, and reworked for the dialogue in this paper. In doing so, we have taken essential steps towards unifying terminology across different research traditions and further exploring the implications of embodiment for science education research. Crucially, we have also demonstrated how science education researchers with similar interests in embodiment and neighboring theoretical perspectives can look at the same data set and reach different conclusions regarding the underlying factors that drive the learning process. Our dialogue is, therefore, a valuable reminder of the importance of considering multiple perspectives when interpreting and analyzing data from embodied perspectives.

Naturally, science education research cannot be divorced from its practical implications, and the wish to understand the fundamental role of the body in science learning has practical implications for improving and assessing the teaching and learning of science. There are numerous ways to incorporate embodied perspectives into science education practices, and the growing body of literature in this area is a testament to the relevance and diversity of such attempts (e.g., Amin et al., 2015; Azevedo & Mann, 2018; Danish et al., 2020; Euler et al. 2019; Hardahl et al., 2019; Kersting et al., 2021; Lindgren et al., 2014; Macrine & Fugate, 2021; Tang, 2022; Tscholl et al., 2021; Weisberg & Newcombe, 2017). Each embodiment tradition will likely suggest different pedagogical designs, assessment approaches, and learning cultures, with their own strengths and weaknesses.

Understanding the underlying assumptions of the three traditions can help science educators choose appropriate strategies for their specific teaching and learning context. For example, if a policy initiative asked science teachers to introduce more embodied learning activities to their classrooms, we would expect to see a variety of activities based on the teacher's particular stance towards embodiment. A science teacher inspired by cognitivist ideas might emphasize the internal mental processes involved in learning science and try to strategically activate productive image schemas during instruction. In the classroom, this could lead to a focus on kinesthetic activities (Bruun & Christiansen, 2016) or conceptual metaphors (Niebert et al., 2012) as the entry points for students' construction of science concepts, with assessment centered on multiple choice exams, knowledge tests or performance tasks (e.g., model construction) that measure students' individual performance and understanding of scientific concepts and the explanatory power of the models they have constructed. A science teacher following a social-interactionist interpretation of embodiment will view science learning as a social and collaborative process and might look for group activities to get students in movement and talking to each other.

In the classroom, this could lead to group projects where students embody science phenomena to develop their scientific understanding in embodied interactions (Close & Scherr, 2015; Danish et al., 2020; López-Incera & Dür, 2019), with assessments centered on group performances and the students' use of movement and gestures (Lindgren & Johnson-Glenberg, 2013). Finally, a phenomenologically inclined science teacher might invite students to bring in their everyday lived experiences and identities from outside school and build on these in the classroom setting or have them reflect explicitly on how they use their bodies through tinkering with materials, movement, and body positions to produce and stabilize physical phenomena (Hardahl et al., 2019). Assessment questions may invite students to reflect on their subjective experiences that justify why and how they come to know science and probe their first-hand experiences of how it feels to be engaged in scientific practices (e.g., acknowledging students' visceral response of disgust when performing dissection of a calf eye in biology class, Orlander & Wickman, 2011). In sum, the particular stance science educators take towards embodiment will necessarily inform their choices about classroom activities and assessment practices, and it is crucial to understand the implicit assumptions of each tradition.

In conclusion, we believe that a deeper understanding of the connections, convergences, and complementarities between our traditions will stimulate more productive work on developing an integrated approach towards embodied science education—or continuing on different paths that have been better illuminated by our conversation between traditions.

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Data Availability Transcripts of the episodes are available in a previously published manuscript (Euler et al., 2019).

Declarations

Ethics Approval The authors declare that there was no need for ethical approval because the paper is based on a previously published transcript of an episode (Euler et al., 2019). No new data was collected, and no original video data was shared among the authors.

Conflict of Interest The authors declare no competing interests.

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