Physics Education Research as a Multidimensional Space: Current Work and Expanding Horizons

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Abstract:

Over the last several decades, Physics Education Research has abundantly grown in both quantity and kind. With our field growing in so many directions, we have an opportunity - and responsibility - to pause and take stock both of where we’ve been and where we might go in the future. In this work, we draw on our experiences within the broader field of education to construct a multidimensional map of the space of research. For individuals, this map can provide an entry point into the vast and complex world of educational research. For our field, this map allows us to both systematically explore the current state of our field, and identify some ways we might purposefully expand moving forward. We conclude by highlighting the numerous factors that play into the multidimensionality of our research, and how this multidimensionality can drive our research trajectories forward.
1. Introduction

Since McDermott’s Millikan lecture in 1990, the field of Physics Education Research has expanded into what may appear to be a boundless, chaotic system. In terms of numbers, those 30-odd years have seen an incredible rise in the number of papers published for the Physics Education Research Conference—from approximately 30 in 2001 to over 100 in the most recent proceedings. In terms of focus, we have seen papers from understanding undergraduate student conceptual learning and developing instructional materials to support it, to exploring how faculty and instructors make sense of their pedagogy, to unpacking the experiences of minoritized students. PER has abundantly grown in both quantity and kind.

When a field grows so profoundly, we should expect (and hope for!) development in the nature of the work itself. Researchers with different identities can and should have different foci and approaches to exploring those foci. Further, those differences should be celebrated, as they are precisely what lends texture and richness to our field. In fact, we suspect it is a deep appreciation of this richness that led to this special issue. With our field growing in so many directions, we have an opportunity - and responsibility - to pause and take stock both of where we’ve been and where we might go in the future.

How, then, can we get a handle on “the state of things” in PER? We suggest our field needs a map. Such a map can help us understand the complexity and richness of the field by articulating the dimensions along which our work varies and coalesces. Additionally, it can help us recognize which portions of which dimensions we have heavily (perhaps even overly) explored and which portions we have not. Situating ourselves in a map can, in turn, help us as a field decide where to focus future efforts.

But what sorts of dimensions will be most useful for understanding our expanding field? In this paper, we draw on our own experiences as graduate students in two very different departments to motivate our attention to dimensions from the broader field of education research. The main contribution of our work, then, is a map that is grounded in important dimensions from education research and fleshed out with examples from PER. For individuals, this map can provide an entry point into the vast and complex world of educational research. For our field, this map allows us to both systematically explore the current state of our field and identify some ways we might purposefully expand moving forward. We conclude by highlighting the numerous factors that play into the multidimensionality of our research, and how this multidimensionality can drive our research trajectories forward.
2. A Tale of Two Graduate Students

Since the field of PER began to emerge in the early 1980s, it has always been a hybrid field. Many researchers came to it from a pure physics background, but there have also been many who approached it from a background in more general education research. This has remained a pattern over the years; according to Van Dusen, Barthelemy, Henderson's survey of PER graduate students’ educational trajectories, there is a roughly 60/40 split between PER grad students in physics departments vs. schools of education. Tor and Rosemary each took different pathways into and around the field, and it is those different paths that give rise to our claim that distinctions in the broader field of education can help us better understand the current state of PER.

2.1 Rosemary’s Tale

I began my graduate career in physics education within a physics department. In my first two years, I took graduate courses in physics and passed the same qualifying exam taken by my peers studying “traditional” physics. However, upon completing those requirements, I began my research in physics education within a very strong research group. In addition to having at least four senior personnel who were active members of the national PER community, numerous visiting scholars spent time thinking with us during my five years in the program, and the community of graduate students was curious, thoughtful, and active. My formal introduction to the field of PER occurred when I attended the weeklong International School of Physics “Enrico Fermi” in Varenna, Italy. There I heard the “giants” in the field give multiple talks, laying out their own research programs and potential future directions for the field. It was transformative both intellectually and personally; I developed a stronger understanding of the field of PER and its scope, and also developed my identity as a physics education researcher.

Following that conference, my advisor encouraged me to take a year “to just read stuff” and follow paths that interested to me. While this task was extremely overwhelming and at times frustrating, I had the opportunity to read scholarship from philosophy of science, educational psychology, linguistics, and cognitive science. As my years in graduate school went on, and later as I accepted a postdoc in the field of the Learning Sciences, I waded farther into the vast sea of generalized education research. For me, this work illuminated theoretical mechanisms that could be driving the student physics learning I had spent hours watching in video.
As my lens broadened from PER to educational research writ large, I began to see physics learning not as a unique phenomenon, but as a particular instantiation of larger educational systems and dynamics. This realization was freeing for me as a researcher, because it meant that I didn’t have to “go at it alone.” My research community, rather than being only those who understood and studied undergraduate level physics, now included scholars with a variety of backgrounds and areas of expertise all exploring an interrelated set of teaching and learning phenomena.

2.2 Tor’s Tale

I, too, started in a physics department, but there was no PER group at my university. As a “pure physics” graduate student I did all of the usual physics grad things (completed graduate-level physics courses, passed the qualifying exam, did research in a lab) but found I spent more time thinking about the physics teaching and learning in my courses than the physics content itself. At the time, my physics department was not supportive of PER, but Rosemary had just joined the science education faculty in the school of education. So, feeling compelled to pursue PER, I took my physics master’s degree, transferred to the school of education, and enrolled in the Ph.D. program there.

Within the school of education, I took numerous graduate education courses, which introduced me to the broad strokes of education research—various theories of learning, educational research approaches and methods, issues of power and equity, and curriculum theory. From there, I gradually narrowed my focus to PER, ending with a solidly PER-style dissertation focusing on undergraduate sensemaking in introductory physics. So, although I came from a physics content background, my ways of thinking about and doing research were shaped by the education courses I took, and it was only later that I became acquainted with the research traditions within PER.

This path was useful for situating what I was reading in PER within the context of teaching and learning more generally. For example, theoretical frameworks are fundamentally built in to general education research; in fact, in my graduate courses we were taught from day one to distinguish between different types of frameworks (theoretical, conceptual, analytical) and how each shaped and informed the research process. Courses like the history of science education also helped me to see the ways in which our current ways of thinking and doing research emerged historically over decades of refinement. And, by studying the actual practices of teaching and learning through courses on curriculum design and the learning sciences, I was able to reflect on the purpose of all of this research in PER. In this way, my pathway highlighted
how I needed PER to give meaning and specificity to the complex landscape of schooling explored in the general education literature.

2.3 Looking Across the Two Pathways

In our tales of our research careers, we have explicitly differentiated between our experiences in PER and in education research. We do so because although there is clear overlap in the two fields, they are also structurally distinct from one another. PER is typically situated in and around physics departments, whereas general education often has its own school and sub-departments within that school. Many of us seeking tenure in one or the other of these departments receive clear messages about the distinctions between the fields. Those distinctions are defined and accentuated by the different journals for PER vs. general education research, as well as different meetings and conferences.

Separating our experiences in the two communities allows us to articulate how our experiences with education research helped us as scholars make sense of PER, and our own place within PER. For Rosemary, education research helped her identify general theories and frameworks for making sense of physics learning phenomena. For Tor, education research helped him establish methods of inquiry most suited to explore his interests within PER. For both Tor and Rosemary, our own expertise in physics, while an asset for understanding the disciplinary specificity of physics learning, can also be a blind spot that prevents us from recognizing dynamics inherent in that learning. In that case, familiarity with the general education research exposed us to educational systems and norms not immediately apparent to a successful “insider” in the field. For each of us, research in general education helped us understand our research in PER.

We suspect many readers agree with us; surely gaining insights into our work in PER by bringing it into conversation with broader education research is a good thing. But how can we go about doing so? The age of the field of general education research, coupled with the incredible number and diversity of researchers in that field, makes the sheer volume of work it has produced insurmountable by any single researcher. And even if we could read all of the research, making sense of it all and situating our own work within it would be impossible. Thus, even though we might want to use education research to help us understand our own work in PER, it is not clear how to do so. We suggest there are two possible approaches: leveraging individual scholars or leveraging organizational frameworks.

2.3.1 Leveraging individual scholars. One way we might get help using education research to situate our own work would be to rely on an individual scholar to mentor
us. To do so, we might ask someone who is already familiar with a body of work that interests us to point us to the “best” or “seminal” articles from the field to read. We might do this one-on-one, by sending an email or introducing ourselves at a conference, or by taking a course with that person at our universities.

Rosemary’s graduate tale provides some insight into this approach. Her graduate advisor was jointly appointed in the physics and education departments, and as a result she was regularly introduced to scholars on campus who could mentor her in applying educational research to her area of interest in PER. Additionally, since her advisor was himself a graduate of a school of education who attended conferences outside of PER, he sent her to attend general education research conferences (American Educational Research Association, National Association of Research in Science Teaching, and International Conference of the Learning Sciences) where she extended her network of education scholar mentors.

But Rosemary’s tale, and any approach that relies on leveraging unfamiliar scholars to support us in navigating new literatures, can only be successful when it takes place within a network of privilege. Specifically, this approach requires that one (a) knows who to ask to be a mentor, (b) has the positionality to feel comfortable asking that person for help, and (c) has the social capital to get a favorable response from that person. Rosemary had access to all of these things because of the “pedigree” of the graduate research program to which she was accepted.

For example, she knew who to ask and felt comfortable doing so because her group’s substantial amount of federal grant funding (in and of itself related to the positionality of her advisors) brought visits from a wide variety researchers in the form of colloquia presenters and advisory board members. One of those advisory board members later became her postdoctoral advisor and intellectual mentor. Further, she had the social capital to get a favorable response from these mentors in part due to her identity as an upper-middle class, White student. Her socioeconomic status allowed her to focus exclusively on obtaining the grades necessary to get a fellowship to graduate school without having to balance the stress and pressure of a job. Her Whiteness meant her peers and professors unquestioningly maintained high expectations for her, including the assumption that she would attend and succeed in graduate school.

This brief story highlights how not all researchers can leverage individual scholars to help them use education research to understand their work. Instead, it was – at least in part - her privileged identity, coupled with the privileged status of her graduate
program, that gave her the opportunity to identify, meet, and engage with potential mentors to support her navigating the world of education research.

2.3.2 Leveraging organizational frameworks. Not all graduate students, nor even all researchers, have this privileged access to mentors who are familiar with education research. Even those who do may find their mentors are not familiar with the portion of education research they need/want to explore in their work. What then are they to do? How can they bring their work in PER into conversation with work from general education?

Tor’s graduate experience offers some insights here. In taking courses on curriculum theory, Culturally Relevant Pedagogy, and the history of education, he was able to begin to see how different lines of research fit together (or not!), and where his own interests lay within all those pieces. These courses defined particular sets of literature as “related” and often positioned the theories of those courses in relation to other literature. In short, his courses in the school of education provided him with a framework for understanding the field.

What we want to highlight from Tor’s experience is the value of having some external structure (in Tor’s case, course titles and collections of readings) to navigate the wide variety of research. Substantial research demonstrates the value of having organizational frameworks for learning, and we propose the same mechanism might be useful in learning how to find connections between general education research and our work in PER. In this work, we construct such an organizational framework; a set of dimensions individual researchers, and we as a field, can use to bring order to what can feel like the chaos of the field of general education and its relationship to our own work in PER.

By providing a starting point for scholars as they seek to understand where their work fits into the broader landscape, we are hopeful that such a map might alleviate at least some of the privilege currently required to navigate between these two fields. But that does not mean that privilege is not infused in the map we present. Specifically, the set of examples we survey in each dimension are merely a selection of those papers with which we are familiar. This approach perpetuates a “rich get richer” model of education citations. We have read those authors whose work is privileged in the field, and in citing it here we are making it even more privileged. Thus, even the map we provide as an access point for less-privileged scholars is perpetuating the system of privilege to which they do not yet have access.

This citation cycle is problematic for many reasons. First, many of the authors are “foundational” precisely because they were White males who examined the world
from a position of privilege that appealed to other White males in the field. Second, it is likely that there are other, less-cited authors whose work speaks just as well, if not better, to the dimensions we explore. Third, while we have tried to avoid it, the research we cite is undoubtedly skewed toward and filtered through our own orientations and approaches. Here we can only acknowledge this bias in our survey of the literature, and highlight that in the sections on expanding PER, we take extra care to focus on emerging scholars whose work may be less-cited, but not less important, for the field. We hope this work will open conversational opportunities for other researchers to question our choices of examples, and for “progressive” scholars to move into the “central” space of our field.

3. Education Research as a Multidimensional Space

Our purpose in this work is to develop a map – using dimensions from the broader field of educational research - that can be used to situate the work of PER. As our personal stories above are meant to show, we intend this map to be useful for individual researchers (such as Tor and Rosemary) seeking to understand where they fit within a broader context. Additionally, we will use this map in the rest of this paper to take stock of where we are as a field.

3.1 Articulating dimensions of research

When we set out to construct a map of the educational research, we were faced with the quandary that there is likely an endless number of ways to carve up the literature, and different scholars would likely cut it up in different ways. However, our goal was to select categories that meaningfully define and differentiate between different strands of work in education, and in PER in particular. In considering potentially relevant dimensions, we identified a variety of categories found in manuscripts, journals, conferences/societies, and standard educational coursework.

- **Manuscripts:** There are a set of standard sections that are at least tacitly expected to help orient the reader to manuscripts for publication. Some journals or conference proceedings (e.g. American Educational Research Association) explicitly mandate sections to include, such as motivation, theoretical/conceptual framework, and methods (including study population and context).

- **Journals:** When submitting a manuscript to any journal, authors typically select key words to help readers identify potentially meaningful articles. For some journals (e.g. Journal of the Learning Sciences), authors are asked to
select key words from a variety of categories such as methods/methodology, population/age of learners, content area, and topic/phenomena.

- **Conferences/Societies**: Education researchers attend conferences for societies that are defined in different ways. Each definition can be understood as a category for members. Common types of categories include methods/methodology (e.g. Qualitative research in education), domain (e.g. National Council for Teachers of Mathematics), contexts of research (e.g. Society of Research on Child Development), theoretical frameworks (e.g. Jean Piaget Society).

- **Educational Courses**: The coursework in education departments is designed to introduce new students to the various strands, or categories, of work in the field. Looking across course offerings from our previous and current institutions revealed distinctions between topics, epistemologies, methods and methodologies, populations and contexts, and theoretical frameworks.

In addition, we followed the work of educational philosopher Crotty who, in his book on *The Foundations of Social Research*, defines the four basic elements of the research process as methods, methodology, theoretical perspective, and epistemology. For the final map presented here, we selected dimensions that appeared as categories in several places, and confirmed they would be useful to PER researchers in the sense that our field’s work showed at least some variation within the category. In the end, we articulated seven dimensions of education research that play into and emerge in the design, conduct, analysis, and write up of a study.

We highlight how we selected these dimensions for the sake of transparency, but need to acknowledge that the selection was not an “objective” process by which we identified the dimensions of educational research. Instead, the dimensions we use are a set among many that we (Rosemary and Tor) find valuable for making sense of the field. In that way, these dimensions still necessarily reflect our own perspectives and lenses, or, phrased differently, our assumptions and biases. Thus, here again we find the effects of privilege in the field. We were invited to write this article because Rosemary, in particular, has been positioned as a person who “knows things” about education research. As such, her perspective/biases (and those of her graduate student) are given more status than others in the field who were not invited to write in this space. Here we can only recognize the privilege and power we have, and (hopefully!) use it to create space for purposeful conversation around meaningful dimensions of work in our field.

To support our analysis of the literature in terms of these dimensions in Section 4, in we organize the dimensions in order of familiarity; we expect most of our readers will
be more aware of the initial dimensions we present and perhaps less so with the later ones. Additionally, we also organize the dimensions in terms of their relationships to one another, from least to most foundational in our research (Figure 1). We elaborate how these dimensions are connected in Section 5.

![Figure 1. Dimensions of Education Research explored in this work](image)

While we believe these dimensions support delineation of key differences in research, we want to acknowledge that “defining” any single study or a field of research in this way inherently reduces the complexity and nuance of the work. Categorization is always a simplification. We do not intend this categorization scheme to take the place of careful exploration of the literature relevant to the work of individual scholars; we hope readers will seek out the complexity lost in our map. However, we nonetheless present these dimensions as a way to help readers orient themselves both to the larger field of education research, and to our field of PER in particular.

### 3.2 Touchstone Examples of Dimensions from Science and Mathematics Education Research

To describe these dimensions for those who may be less familiar with them, we use two popular papers from the broader field of education. Rather than selecting papers from across the entire field of education, we chose two papers from the subfields of science and mathematics education because we suspect those are most directly relevant for PER. Further, we chose these papers both because they are highly cited and influential papers in the field of general education research (see our caveat about this “rich getting richer” approach in section 2.2.1), and because they differ in nearly every dimension presented below.

The first paper we selected comes from science education (a field many of our colleagues in PER are familiar with) and examines students’ knowledge and beliefs about science (something the field of PER has devoted a fair amount of intellectual
effort toward understanding). Lederman, Abd-El-Khalick, Bell, and Schwartz’s work comes out of a long line of research aimed to understand and probe how K-12 students view the Nature of Science (NoS). Since the early 1990s, there has been great interest (especially in educational standards and reform efforts) in helping students understand what it is that differentiates science from other types and ways of knowing, which they call the Nature of Science (although the authors contend that, since science isn’t a single, coherent domain, it’s best to just refer to it as NoS, not the NoS). In this paper, the authors present and justify the development of an assessment of students’ views on the Nature of Science. Their goal is three-fold: first, they unpack the different aspects of science that students should understand, the different aspects of NoS that provide the basis for their study. Second, they argue that previous multiple-choice assessments of student views of NoS are insufficient and show how a more open-ended assessment called the Views of Nature of Science Questionnaire (VNOS), based partially on student interviews, provides a more accurate picture of student understanding of NoS. Third, they justify the validity of their assessment, based on extensive application and refinement, and provide suggestions for implementation.

The second paper we selected comes out of sociology, and is commonly thought of as one of the foundational works in the development of Situated Cognitive Theory. Lave, Murtaugh, and de la Rocha’s work came at a point when educational researchers were increasingly questioning the validity of decontextualized studies of learning. Their study is a direct response to this critique, and it focuses on the ways in which context affects mathematical reasoning and performance, specifically looking at how grocery shoppers use arithmetic in supermarkets. The authors had the shoppers carry tape recorders as they went about their shopping, asking them to “think out loud” while also following them around and engaged them in conversation about what they were doing. Using this data, they investigate the ways in which the shoppers used arithmetic to make price comparisons in order to decide what to buy. They then compare the shoppers’ performance in the supermarket to their performance on a paper-and-pencil arithmetic test, finding that shoppers performed much better in the grocery store than on the test. Based on this finding, they tease apart some of the strategies that the grocery shoppers used to quickly and accurately make price comparisons, such as simplification and rounding, multiple rounds of calculation, and repeated checks and updates of their results.

4. Dimensions of Education Research

In what follows, we use the dimensions of education research in our map to explore the current state of our field, and identify some ways our field might purposefully
Given the large number of dimensions, we use a parallel structure across the sections to support readers in “wading through the weeds.” Specifically, in each of the sections we (a) define the dimension, (b) briefly survey the breadth of the dimension within the broader fields of science and mathematics education research, (c) highlight how the dimension plays out in the two exemplar papers, (d) use multiple examples of current work to describe how the dimension is populated within PER, (e) suggest potential ways PER might expand along the dimension by foregrounding the work of several forward-thinking scholars.

4.1 Disciplinary Dimension

The first dimension is disciplinarity. When we define ourselves - even just in name - by the discipline we study, we make the discipline (or subdiscipline) we explore a central dimension of the work. Part of defining the disciplinary dimension of our work is to delineate, both for ourselves and others, the domains in which we expect our arguments to apply. Further, doing so allows us to make automatic connections to other researchers we want to engage in scholarly conversation around our ideas.

In the broader field of education research, this disciplinary dimension is often quite coarse. Work is defined as, for example, science education research,\textsuperscript{17,18,19} mathematics education research,\textsuperscript{20,21,22} or teacher education research.\textsuperscript{23,24,25} Along this dimension Lederman and his colleagues’ work is clearly science education.\textsuperscript{15} Lave and her colleagues’ work is ostensibly mathematics education;\textsuperscript{16} it focuses on people’s ways of thinking and reasoning about arithmetic and problem solving with numbers.

However, there are also some complications to this seemingly straightforward dimension. First, in some cases, disciplines may sub-divide into smaller categories and in other cases may not. For example, Lederman and his colleagues would not consider their work to be specific to, say, biology, but instead want to be identified as science generally.\textsuperscript{15} Second, there is research that cannot be defined by a single disciplinary dimension, either because it is a phenomenon that reaches across multiple domains (e.g. studies of teacher identities in literacy and mathematics\textsuperscript{26}) or because it is the phenomenon itself is not disciplinary (e.g. perpetuation of ideology in schooling\textsuperscript{27}). Lave and her colleagues’ work falls into this category;\textsuperscript{16} although she
demonstrated the situated nature of thinking in the realm of mathematics, the theory of Situated Cognition is understood to hold across multiple domains.

4.1.1 How is PER distributed along this dimension? PER as a field is defined by a discipline, and in doing so it delineates itself from other disciplines such as Biology Education Research or Chemistry Education Research. But within PER, there also exist strong sub-disciplinary boundaries. There are distinctions between introductory physics\textsuperscript{28,29} and advanced-level physics\textsuperscript{30,31} and distinctions within each of those between kinematics\textsuperscript{32,33} and electrostatics\textsuperscript{34,35} or quantum mechanics\textsuperscript{36,37} and electrodynamics.\textsuperscript{38} For example, Podolefsky and Finkelstein’s work explores conceptual blending in the sub-discipline of electricity and magnetism,\textsuperscript{39} while Scherr’s work describes different theoretical models of student knowledge of simultaneity in the sub-discipline of relativity.\textsuperscript{40}

As in the general education research, there are also complicating cases within PER. For example, although research on LA’s often occurs within the context of physics courses,\textsuperscript{41,42} the general insights from that work are typically not limited to the discipline of physics.\textsuperscript{43} Further, there are those who study phenomena that may not be inherently disciplinary such as a sense of belonging.\textsuperscript{44}

4.1.2 How might PER expand along this dimension? One option for PER to extend its work along this dimension is to carefully identify the important sub-disciplines our work needs to cover. For example, there is a heavy amount of work in introductory sub-disciplines such as energy,\textsuperscript{45} but comparatively little work in modern physics. Recently, scholars in our field have pushed to broaden our scope in this dimension, and we encourage that work to continue.

Additionally, though, we suggest that we as a field should continue to identify ways to shift and stretch our work so that it extends beyond the bounds of what we have traditionally called “physics.” For example, researchers at the University of Maryland have begun to explore interdisciplinary connections between physics and biology.\textsuperscript{29,46,47} Extending PER along this dimension in this way has several affordances. First, it allows our work to be more widely read, thus giving us more opportunities for feedback, collaboration, and impact. Second, it provides us with a greater set of literature to inform our thinking. And finally, it allows us to see continuities with other work we might otherwise miss.

4.2 Phenomenological Dimension

Beyond the general domain or discipline of research, the next most obvious dimension is the phenomenon—that is, “what are we studying?” When building a
study, figuring out what phenomenon to study is perhaps the first thing we tackle. But, as anyone who has done educational research well knows, picking one’s phenomenon is usually more complicated than it first seems. This may be because the general class of phenomena we are interested in—teaching and learning—are incredibly complicated, so we can at best study only specific aspects of them. The importance of this dimension, then, lies in the process of narrowing one’s focus to one or more specific aspects of teaching and learning—“nailing down” what we are trying to study. This, in turn, makes the process of studying teaching and learning more manageable, narrowing the scope of one’s study to reasonable levels.

Within mathematics and science education research writ large, there are a huge range of phenomena under study. This, in part, is because over time, the constructs of “knowledge” and “learning” have become incredibly expansive, extending from content learning of school subjects,48,49 to constructing meaning in everyday life,50,51,52 to changing systems that constrain and enable individual learning.53,54 Lederman et al. and Lave et al.’s works nicely illustrate the breadth of this dimension.15,16 Lederman et al.’s work focuses on students’ multifaceted views of the Nature of Science through the lens of their developed assessment.15 In contrast, Lave et al. are interested in how people use math in everyday life, beyond the standard arithmetic used in formal educational settings;16 that is, they are less interested in people’s specific knowledge or learning processes, and more in the structures, systems, and norms of interaction that affect these processes.

Together, these two studies illustrate a key aspect of this dimension for the field of general science and mathematics education research: some educational phenomena include classroom learning and some do not. In other words, research in general education takes an expansive view of the system of learning, such that phenomena occurring outside of classrooms reflect back on and drive what we see in classrooms. The phenomena we see in classrooms are built from and around what occurs outside of classrooms, across one’s lifespan and in different places.

4.2.1 How is PER distributed along this dimension? Within PER, we also investigate a wide range of phenomena, but most of these are classroom- or institution-based. That is, the phenomenon that we commonly investigate are grounded in experiences of those in formal teaching and learning situations. For much of our history, most of our research was focused on student misconceptions,55-59 assessment,60,61,62 and educational innovations,63,64 all of which took place in, and was used in, classrooms.
Since the early 2000s, a great deal of focus has turned to student attitudes and beliefs about physics,\textsuperscript{65,66,67} models of student cognition and understanding,\textsuperscript{68,69,70} interactions of identity and social structures within physics,\textsuperscript{71,72,73} studies of institutional change,\textsuperscript{74} and transitions from 2- to 4-year colleges.\textsuperscript{75,76} However, in nearly all cases the phenomenon under study is found within or around formal learning spaces in institutions of higher education.

4.2.2 How might PER expand along this dimension? We would argue that PER might expand along this dimension by broadening what constitutes physics learning and the phenomena we consider relevant to physics learning. Specifically, although formal physics learning is central to our field’s mission, PER could push ourselves to explore phenomena that do not immediately “look like” physics. For example, Hinko et al.’s work examining interactions between university educators and K-8 children in an after-school program is a push in this direction.\textsuperscript{77} They make a compelling argument that the teaching modes used in those spaces may impact what goes on in more formal learning spaces. As we consider expanding our work along this dimension, it may become necessary to expand what we consider the beginnings—and driving factors—of physics learning.

4.3 Population Dimension

As researchers, another important part of our work is identifying the population we want to study. For some of us, a commitment to a certain population actually drives the phenomenon we choose to study. In other cases, it is the other way around; we select a phenomenon we are interested in and then select the population that will help us best understand that phenomenon. Either way, this dimension answers the question “who am I studying?” and often extends to “who do I need to study in order to convince others of my argument?”

Identifying our population of study is a one way in which we define the context of our work. In doing so, it sets boundaries on the kinds of arguments we can make and which researchers may be interested in our work. Further, how we define our population conveys to others a great deal about the assumptions we make in our work. For example, defining our population as undergraduate physics majors sends a very different message to our readers than defining our population as largely White, male physics majors.

Across the general mathematics and science education literature, in the same way, there is much variation in phenomena, there is also large variation in the populations that are studied. This range includes ages of young children,\textsuperscript{78,79} adolescents,\textsuperscript{80,81} and adults.\textsuperscript{82} It includes professions such as students,\textsuperscript{83,84} teachers,\textsuperscript{85,86} and school...
leaders,\(^{87,88}\) as well as non-school-based professions.\(^{89,90}\) It includes various units of participants from individuals,\(^ {91,92}\) to learning communities,\(^ {93,94,95}\) to families,\(^ {96,97}\) to specific cultural and ethnic groups.\(^ {98,99}\) It includes participants of varying race,\(^ {100}\) gender,\(^ {101}\) and first language.\(^ {102}\) Lederman et al. use the VNOS survey in school settings, with high school and college students in science courses, as well as with undergraduate pre-service teachers;\(^ {15}\) the population was selected because of its role in schooling. In contrast, Lave et al.’s work focuses on adult grocery shoppers;\(^ {16}\) the population was selected precisely because of its lack of connection to formal schooling. Only Lave et al. include demographic information about their population (age, income, education, gender, and first language).

### 4.3.1 How is PER distributed along this dimension?

Kanim and Cid’s work documenting the demographics of our research provides a systematic picture of our distribution along this dimension.\(^ {103}\) In PER, our decisions about population have largely come from our initial focus on improving undergraduate instruction. We have focused on students enrolled in those courses not only because they are of interest to us, but also because—in our roles as instructors in those courses—we have relatively easy access to them. Unlike general education studies that often have to develop strategic recruitment and compensation strategies for their studies, PER can typically access large numbers of undergraduate students from a variety of courses each semester.\(^ {28,104}\)

As our field has grown, so have the populations we have studied. We have expanded to include upper-division students,\(^ {35,105,106}\) non-majors,\(^ {29,107}\) graduate students,\(^ {10,37,108}\) K-12 teachers and students,\(^ {109-112}\) instructors/TAs/LAs,\(^ {113,114}\) as well as institutions themselves.\(^ {42,74}\) This work has provided us with a great deal of insight into the dynamics of physics teaching and learning beyond introductory courses, and has opened up the space of who “counts” as a learner of physics. However, as Kanim and Cid’s thorough examination of the demographics of our field’s research demonstrates,\(^ {103}\) much of our work continues to examine non-diverse, privileged populations.

### 4.3.2 How might PER expand along this dimension?

As Kanim and Cid carefully document,\(^ {103}\) our studies have disproportionately examined populations from Western, Educated, Industrialized, Rich, Democratic (“WEIRD”) societies (Ding & Zhang’s work with Chinese teachers is a notable exception\(^ {115}\)). This focus on a WEIRD,\(^ {116}\) predominantly White population is not unique to PER; the field of educational psychology within the broader education literature has begun to reflect on what it means that the vast majority of what they “know” about human psychology and behavior comes from studies of a very narrow, privileged slice of the world.\(^ {117}\)
PER is fortunate to have a number of scholars who have already pushed us to expand along this dimension. Critical new research the experiences of minoritized students in physics.\textsuperscript{7,10} Even further, some scholars are rightly demanding our field not only expand our populations of study, but also destabilize our normalization of Whiteness, cis-gender, and heterosexuality in our research.\textsuperscript{118}

PER could also expand our work in this dimension by examining features of our population that arise from their non-student/teacher identities (even if we still chose to recruit them from physics courses). Often in our own work, Tor and Rosemary find themselves interchanging the terms “students” and “participants.” This interchangeability arises because the primary inclusion criteria for our studies is that participants be students in science courses. What if instead, we invited people (possibly students) to participate because they demonstrate physics-like reasoning in their workplace or when they talked to their children? This type of expansion may necessitate an explicit discussion within our field of what makes something “physics,” and such a discussion would likely reveal a lot of our tacit assumptions and biases that are worth making articulate for one another.

4.4 Contextual Dimension

When designing their research, scholars must decide where they will look to study their phenomenon among their population. Specifically, they must make decisions about the context of their work by answering “What environment do I need to explore/design to make my argument?” Answering this question involves articulating the “identifiable, durable framework for activity with properties that transcend the experience of individuals” as well as “the constructable, malleable nature of the setting in relation to the activity of particular [participants]” (p. 71-72).\textsuperscript{16} Context involves features both independent of participants (e.g. physical arrangement of space) and tied to participants (participant expectations or roles). As a result, for many scholars, their contexts and participants are inextricably overlapped and linked.

Decisions about context are crucial to our work. First, they embody assumptions we have about what “matters” in the phenomenon we are studying. For example, in Tor’s work examining undergraduate student sensemaking in the context of interviews, he makes the tacit assumption that the phenomenon of sensemaking is approximately the same in interviews as it would be in the classroom. Second, contexts both support and constrain what we are able to understand about the phenomenon we study. In Rosemary’s work examining pre-service teacher learning in the context of her methods courses, she can only experience and make sense of interactions of predominantly White, middle class women. For readers, our decisions about context
help them understand whether and how our arguments are generalizable or applicable to their own work.

There are multiple levels of context, all nested within one another, that influence the arguments we can make in our work. Here, we focus on the microsystem: the immediate setting of the participants that is “complex of relations” involving “the factors of place, time, physical features, activity, participant, and role[s]” (ibid., p. 514). This portion of context is the one most commonly given by science and mathematics education researchers and entails descriptions of professional development programs, classroom activity, teacher preparation programs, interviews, informal learning environments, or everyday spaces. For example, Lederman et al. quickly describe a variety of microsystems in which their survey can be used, and suggest specifically that the context involve “controlled conditions (e.g. in class under supervision)” (p. 511). In contrast, Lave and her colleagues spend a full five pages describing the supermarket microsystem of their study, carefully articulating its imposed and malleable features and what that means for their analysis.

In terms of the microsystems explored in mathematics and science education, we often distinguish between natural and experimental contexts. Dunbar refers to this as the difference between studying phenomena “in vivo” as they naturally occur, or “in vitro” in a laboratory setting designed to make the phenomenon occur. Lave and her colleagues’ research in supermarkets seems a clear case of in vivo work. Indeed, the main purpose of her study was to explore mathematical thinking in spaces in which it occurs naturally. Lederman et al.’s context is less clearly in vivo or in vitro. Do we consider schooling to be a “naturalistic” context? It is clearly not naturalistic in the way the grocery store is, but it is clearly more naturalistic than, say, an interview or the typical laboratory-based settings common in educational psychology.

4.4.1 How is PER distributed along this dimension? In terms of the in vivo/in vitro distinction, PER is well distributed along this dimension. Our field has relied heavily on in vitro-like contexts to explore a range of phenomena. For example, we have made extensive use of both interviews and surveys. These in vitro contexts have been invaluable because they have allowed us to create more regular, sustained opportunities to observe and study our phenomena than we would naturally have access to. Additionally, there are a range of studies that observe and understand participant experiences of physics in vivo as it occurs in formal schooling.

4.4.2 How might PER expand along this dimension? There are multiple opportunities for PER to contextually expand. First, we could (and indeed should!) add new
microsystems to our in vivo studies. Again, we have many scholars pushing us toward contexts of higher education outside of 4-year, predominantly White-serving institutions such as 2-year institutions of higher education and/or Historically Black Colleges and Universities (HBCUs), Minority Serving Institutions (MSIs), and Hispanic Serving Institutions (HSIs). However, to date there is little to no work in PER which studies physics teaching and learning outside of the context of formal schooling. What would it mean for our field to expand in that direction as well?

Beyond expanding our in vivo contexts, PER could also begin to explicitly articulate the power and influence of contexts over the arguments we produce. Currently, many of us (Rosemary and Tor included!) merely drop a sentence or paragraph about context into the methods sections of our papers, and do not play that context forward into the substance of our analysis or conclusions. However, Bronfenbrenner describes how macrosystems are an important part of context that “refers to the overarching institutional patterns of the culture or subculture, such as the economic, social, educational, legal, and political systems.” He highlights that macrosystems are not only structural, but also carry norms and ideologies that give meaning to the activity and interactions of the participants. Barthelemy, McCormick, and Henderson explicate the larger contexts of the lives of the female students in their work. Doing so is essential for their - and our - understanding of women’s experiences of microaggression in physics.

For in vitro studies, PER researchers could also begin to address questions about ecological validity of our contexts. diSessa describes how “we do not want to analyze data that are collected under circumstances that relate in problematic ways to the conditions that hold when the processes we supposedly are investigating ordinarily operate” (p. 528). We must ask ourselves, and explicate for our readers, how confident we are that the in vitro studies we design actually create space for a reasonable approximation of the phenomenon we study.

4.5 Methods/Methodological Dimension

In addition to deciding the who, what, when, and where of their work, researchers also need to decide the how of their study. Methods and methodologies are the systematic approaches we take to obtaining data to convince others of our argument. Further, methodological choices impact not only data collection but also data analysis and data presentation. Many of us have “go to” methods that both capitalize on our strengths and seem to “fit” with the phenomena we are interested in studying. For example, Tor’s interest in looking in a fine-grained way at student sensemaking made interviewing coupled with case-study methods the appropriate choice for his work.
Further, interviews were a fairly natural extension of his experience talking with students and working through problems with them both as a tutor and a TA.

Within general science and mathematics education research, methodological choices are extremely diverse. However, researchers tend to classify themselves as either quantitative or qualitative scholars (with some mixed-methods researchers as well). Selecting a particular methodological framework narrows the type and amount of evidence we will have to make our arguments compelling. As such, they are an important part of our research work.

Quantitative methodologies are used to understanding patterns in the complex educational phenomena in the world. To “see” these patterns, these methods involve isolating and reducing the number of variables or factors in data collection and analysis. In data collection in mathematics and science education, this reduction might involve collecting responses to Likert-scale surveys, scores on research instruments, times, or, more recently, computer log files. In data analysis, this reduction involves analyzing counts, frequencies, trends either of already quantized data such as scores, or of codified qualitative data. Lederman et al.’s use of a survey and subsequent analysis of that survey in terms of percent correctness is prototypical quantitative work.

In contrast, qualitative researchers in mathematics and science education are typically not interested in reducing complexity, but instead in revealing it. As such, the methods they use precisely attempt to maintain and understand the full range of features that construct the phenomenon of study. In terms of data collection, qualitative researchers lean toward what can be called “thick” observations. For example, they may observe natural interactions, design and conduct interactions in interviews or think-alouds, or observe activity in purposefully-designed, learning spaces. Their analyses of these data tend to be rich and fine-grained in the form of case studies, discourse analyses, or ethnographies. Lave and her colleagues’ observations and interviews with shoppers in grocery stores are qualitative; their analyses take the form of snippets of transcripts put together to tell a story about shoppers’ mathematical activity.

4.5.1 How is PER distributed along this dimension? We use a fairly standard set of methods and methodologies within PER, both qualitative and quantitative. Typically, methods for data collection include surveys, assessment-instruments, interviews, and participant observation. In terms of data analysis, many studies rely on basic statistical techniques and coding analyses either of written data.
Further, our field uses large-N summary/frequency analyses, discourse analysis, and case-study analysis. 

4.5.2 How might PER expand along this dimension? As technologies change and grow, the number of methods for data collection and analysis increase dramatically. PER could decide to pursue some of these new methods, such as participant collected data with relatively little change in our research designs. However, there are a number of scholars in our field whose work represents substantially newer horizons in this dimension. In the quantitative direction, Brewe and his colleagues’ work using network analysis opened a new set of methods for our field to consider. Additionally, many researchers are working to advance our use of statistical methods for analysis of large data sets. In the qualitative direction, several scholars have pushed our understandings of the modalities we can analyze in video records of student learning.

4.6 Theoretical and Conceptual Dimension

In science, we acknowledge that we do not “see” the physical and natural world except through the lens of the theories and models we have developed to interpret the world. In the same way, in education research we do not “see” our phenomena except through the particular lenses we (explicitly or tacitly) adopt. Instead, we adopt theoretical perspectives as “way[s] of looking at the world and making sense of it” (p. 8). Eisenhart defines theoretical frameworks as “structure[s] that guide research” that are “constructed by using established, coherent explanation of certain phenomena and relationships” (p. 205). For example, both Rosemary and Tor commonly use the theoretical frameworks of personal epistemology and Knowledge in Pieces, also known as the resources framework.

Theoretical frameworks provide us with a set of constructs and relationships between those constructs that create systematicity in our work. They not only help us interpret the phenomenon we observe, but also structure which phenomenon we are able to observe in the first place. For researchers, intentionally selecting a theoretical framework allows us to align our study questions, methods, and analysis and identify research and researchers whose work we use to build and extend our arguments. In doing so, theoretical frameworks give us a language for acknowledging and operationalizing our assumptions. For readers, theoretical frameworks tell us both the stance from which someone approached their research, and something about how they will interpret their results.

Some education researchers—Rosemary included—define themselves more by their theoretical frameworks than by the specific phenomenon, discipline, or population
they study. Communicating and joining with scholars who share a theoretical framework allows scholars to advance their understanding of, and the power of, the theoretical framework itself. As such, it is not uncommon to find mathematics and science education scholars working or presenting together at conferences or in special issues of journals.

Within the wider field of education research there are a massive number of theoretical frameworks to adopt, with new frameworks or refinements to frameworks regularly proposed. Scholars in mathematics and science education use theoretical frameworks as diverse as distributed cognition, sociocultural theory, and critical race theory. Further, each of these theories has been refined for use in science and mathematics education. For example, Vygotsky’s Sociocultural Theory has been narrowed and used as Activity Theory, and further refined into Cultural-Historical Activity Theory. The two focal papers illustrate this diversity: Lederman et al. use a cognitivist framework, viewing beliefs and understandings as properties of individual students. Lave et al., on the other hand, adopt a sociocultural perspective and view knowledge as being situated within activities and contexts, inseparable from the particulars of those contexts.

Once one has chosen a particular theoretical framework, there is still more to do. Since theoretical frameworks are extremely broad, education researchers also must decide which specific concepts from within those frameworks we will use in our studies. The resources theoretical framework, for example, hypothesizes the existence of a huge number of different resources (of various types), but in practice we do not typically categorize all of the possible resources an individual is drawing on. For example, while Lave and her colleagues’ work draws heavily on activity theory, they focus mostly on the role of what they call “setting” within the larger activity system. Other researchers focus on other aspects of activity theory including tools and/or roles and division of labor.

4.6.1 How is this dimension populated in PER? Within PER, there are several commonly-used theoretical frameworks. Within the cognitive realm, scholars have drawn heavily on conceptual change theories and the resources framework. More recently, and largely following a push from Otero, scholars have used sociocultural frameworks to explore the dynamics of physics learning. However, there is also a significant amount of the literature that distances itself from theoretical frameworks entirely, (implicitly) positioning itself as a-theoretical.
4.6.2 How might PER expand along this dimension? There are of course a fairly infinite number of theoretical frameworks (particularly if we include sociology, linguistics, and science and technology studies, all of which have relevance) PER could choose to adopt to expand our work. Some researchers have begun doing so in remarkable ways, and not surprisingly the use of those theories has resulted in new insights about minoritized populations. For example, the work of Traxler and her colleagues use theories of gender performativity from outside of PER to problematize our existing assumptions and research around gender. Similarly, Rosa & Moore Mensah’s scholarship exploring the experiences of successful Black, female physicists draws on Critical Race Theory to recognize our tendencies toward “construction of differences” (p. 3) in our research. Work of this sort not only allows us to understand familiar phenomena in new ways, but also to recognize the complexity of phenomena that have remained hidden by our previous assumptions as embedded in our theoretical frameworks.

Further, within our use of theoretical frameworks, our field could demand clarity from one another around the concepts and constructs we use. Such a process would be akin to clarifying our conceptual frameworks by defining the nature of constructs we typically use intuitively (such as “ideas,” “beliefs,” or “attitudes”). Gupta, Hammer, and Redish’s work on ontology is explicit in its articulation of the constructs. In fact, their purpose in that work is precisely to specify the ontology of ontologies! As our field begins to draw on a larger number of theoretical frameworks, it will become essential that we define the constructs within those frameworks with more precision than we have to date.

4.7 Epistemological Dimension

We have saved the dimension - epistemology - for last, and will take some care in articulating it. When education researchers talk about the epistemology of their research, they are not referring to what many of us in PER think of (personal epistemology made popular by the work of Hammer and Elby). Instead, they are using the term in the philosophical sense to refer to the “what constitutes knowledge or truth?” Specifically, a researcher’s epistemology indicates what researchers consider to be knowable about the world, something akin to “What is it that you know when you say you know?”

While there is a long list of variants in epistemology that are meaningful for education researchers—e.g. positivist, post-positivist, empiricist, interpretivist, hermeneutic, structuralist, postmodernist, and on and on—here we limit ourselves to two main categories: what Crotty calls objectivism and
constructionism.\textsuperscript{14} When researchers differ across the epistemological dimension, it can often seem as though they are talking different languages; one might not accept either the questions or the data of the other. As such, it is important to clarify our own epistemologies.

The first orientation, objectivism, is rooted in the idea that objects, truth, and reality all exist outside of our perception of it. An analogy may be useful; objectivists believe that whether I see/hear/sense/measure a tree falling in the forest, the tree still fell.\textsuperscript{14} In this tradition, data is “collected” and results are “found” (and “reproduced”) because the phenomenon of study is assumed to exist independent of our measurement of it. For example, in Rosemary’s work on mechanistic reasoning, she took people’s words as a direct indication of their cognition, and thus used their words to make claims about what they did or did not know at that given point in time.\textsuperscript{21,25} In that work, she assumed people’s cognition existed in their heads and “lived” outside of the study, waiting for her to “find” it; her intervening to document that cognition did nothing to alter the singular truth of it.

In this epistemological orientation, there is one “reality” and it is the job of researchers to design studies that allow us to get as close as possible to that reality. A wide range of studies in mathematics and science education adopt such a stance toward educational phenomena.\textsuperscript{21,26} Lederman et al.’s survey follows this objectivist epistemology.\textsuperscript{15} In their work, they assume that people “have” beliefs about the nature of science that can be uncovered using their survey. In this work, researchers assume “there is an objective truth we need to identify, and can identify, with [at least some] precision and certitude.”\textsuperscript{14}

The second epistemological perspective, constructionism, is defined largely in opposition to the former stance. Within this orientation, we - as humans - construct our reality historically, sociologically, and perceptually. Hence, the tree may or may not fall in the forest, but our understanding of its fall is what matters. As Crotty describes, knowledge and “meanings are constructed by human beings as they engage with the world they are interpreting” (p. 43).\textsuperscript{14} This perspective does not believe we create truth and reality ad hoc as researchers; instead, we construct meaning in interaction with objects in the world. As a result of that construction, there will be many truths for any given phenomenon, and there is no attempt to refine research methods to get “closer” to the truth. Instead, the product of research is meaning, not truth. Here, data is not “collected,” but “generated,” and what comes from analysis are not “findings,” but “understandings.”
Constructionism - the rejection of a reality independent of our observation of it - is challenging to wrap our minds around. One might be inclined to think that any researcher who studies phenomenon in context is a constructionist. However, the existence of context in a study is an insufficient criterion for constructionism. Researchers must be constructing meaning through the context (constructionism), not merely truth-seeking within the context (objectivism). For example, Lave and her colleagues are not looking to “find” grocery shoppers’ knowledge within that context. Instead, the researchers (not the participants) are constructing meaning through the context of grocery shopping. They describe how their work involves “the very conceptualization of practical [grocery store] arithmetic as a gap-closing [problem solving] process” (p. 94). The researchers take the actions and mental activity of the grocery shoppers and construct that activity as mathematics, with the awareness and acknowledgement that other researchers could construct that activity differently. A range of qualitative studies in math and science education adopt this perspective, constructing meaning around mathematical competence, classroom opposition, scientific/school-based power, and even learning itself.

4.7.1 How is this dimension populated in PER? Within PER, some work assumes there is a reality of knowledge, beliefs, experiences, etc. that exists independently of us as researchers. Concept inventories, and their use as measurements of student knowledge, are prototypical examples of an objectivist epistemology. Other examples include interviews and surveys designed to “uncover” student beliefs. Within this work, the objectivist orientation is clear in the discussion of methods and their limitations. Researchers may focus on how close they think they have gotten to the “actual” phenomenon they want to study. Did the online survey “actually” capture student beliefs? Did the interview questions “bias” the student toward one answer over another so that we cannot say their answer is what they “really” know? These questions all stem from the assumption that there is a reality we can capture independently of our interpretation of it.

Recently, some researchers have started unpacking the experiences of students in undergraduate classrooms. In this work, they acknowledge the existence of multiple narratives around the “reality” of the classroom. Danielak et al.’s work on the sensemaking identity of an introductory engineering student, Michael, is an example. Michael’s experience of his engineering class, as he recounts it in interviews to the researchers, allows us to understand him as an outsider in his community. Michael’s experience as an outsider is constructed through his interactions with the researchers; it is not a reality to be measured.
4.7.2 How might PER expand along this dimension? Establishing, or even recognizing, one’s epistemology can be extremely challenging, because often what we take to be “truth” is so embedded in our ways of being in the world we cannot recognize it. As such, a first step for expanding along this dimension will involve self-interrogation on the part of researchers to establish our own existing, and largely tacit, epistemologies. Once we have begun tackling that (insanely overwhelming!) task, we could begin to talk about what it would mean to expand what we count as knowledge and evidence of that knowledge in our field. Are we comfortable with the idea that we cannot get closer and closer to a single truth? Such a discussion might open up new avenues for understanding (and constructing) the phenomenon of physics teaching and learning.

5. Discussion: Constraints on Multidimensionality

We have described seven dimensions from general education research we believe give us some leverage in parsing and understanding the current state of the field of PER. Those dimensions are: Discipline, Phenomenon, Population, Context, Methods/Methodologies, Theoretical/Conceptual Framework, and Epistemology. We can understand that each dimension represents a decision researchers make (either tacitly or explicitly) when they design and conduct research and make an argument about that research to the field. As a result, any research we conduct is inherently multidimensional.

But should we imagine researchers going down our list and freely making seven independent decisions about their work? The answer quite clearly has to be “no.” Although we as researchers have a fair amount of agency, we are by no means able to freely choose all the dimensions of our work. As one of the reviewers of this piece aptly pointed out, our “choices of frameworks, methods, and phenomena are often shaped by non-research interests such as outside political pressures or underlying cultural views.”\textsuperscript{224} For example, PER scholars in physics departments may face political pressure (in the form of tenure reviews and journal impact factors) to study particular populations (undergraduate students) in particular contexts (calculus-based courses).\textsuperscript{164} Power structures dictate, often in hidden ways, what populations are worth studying, in what ways, and through which lenses. Privilege shapes which portions of the dimensions are worthwhile, significant, and prestigious.\textsuperscript{224} (We wish to be clear that we, as authors, are only just coming to see these hidden forces in our research decisions. We are incredibly grateful to our reviewer for pointing it out, and in fact are frustrated that our privilege puts us in the position of having to speak her insightful words.)
In addition to political and social power constraining our decision making, our own decisions in one dimension inherently reduce and constrain decisions along other dimensions. Although we have described these dimensions—and choices researchers make about them—individually, they are all connected with one another. It would be a mistake to assume researchers can pick and choose along these dimensions in an ad hoc fashion, based solely on preference or convenience. Figure 1 represents one form of that connection; epistemologies necessarily underlie theoretical frameworks, which underlie methods, and so on and so on. As Crotty points out, one’s “theoretical framework [is a]... statement of the assumptions brought to the research task and reflected in the methodology as we understand and employ it” (p. 7, emphasis ours). In this way, our phenomena, methods, populations, and contexts are deeply connected to our epistemologies and theories.

This does not mean that we always explicitly articulate our epistemologies and theories before making other decisions. There are clearly times when we might select our methods or populations first. However, we argue that even when we do so, we have still tacitly chosen a particular epistemology and theory. In fact, precisely this thing occurred for Rosemary in graduate school. When it came time to write the “Theoretical Framework” chapter of her dissertation, she told her advisor (who will remain nameless), that although she knew about the resources framework, she didn’t really think she used it as a theoretical perspective in her work. (Even now this story makes Rosemary—and likely her advisor—cringe!) In response, he (kindly) pointed out the ways in which her work reflected a dynamic model of individual, context-dependent cognition with at least some nod toward a constructionist epistemology. First, her work involved qualitative, discourse analysis of student speech (constructionism). Second, her work took the form of case studies which made claims about what individual students did and did not know (individual cognitivism). Third, her work explored student reasoning in classrooms (context-dependence) and highlighted particular transitions into and out of reasoning (dynamics).

This story highlights how Rosemary’s advisor (tacitly) guided her throughout her research career to maintain consistency across all the dimensions of her work. He did so because not doing so would undermine the very process of research through which we systematically and consistently explore the dynamics of physics education. Tor’s experience is similar but more explicit (perhaps Rosemary is less subtle than her advisor); Rosemary repeatedly pushes him (sometimes to the point of frustration!) to articulate his theoretical and conceptual frameworks such that he can explicitly connect them to his phenomena, context, analysis and claims. The many dimensions of our work are not, nor should they be, disconnected.
The interconnectedness of these dimensions suggests that we as a field must be intentional about whether and how the dimensions in our scholarship align. Rather than seeing a researcher’s commitment to a particular method as preference, we should instead see it as a manifestation of a particular tacit epistemology that the researcher could articulate in their work. Similarly, rather than seeing a researcher’s selection of a particular context or population as a matter of convenience, we might identify in it an underlying theoretical or conceptual framework that is worth making explicit. Articulating these tacit connections among the dimensions of our work, then, will be essential for others as they attempt to understand, and potentially reproduce, our work.

We must also attend to instances when our research embodies what may appear to be contradictory multidimensionality. For example, it would be odd, and indeed completely inappropriate, for someone with a constructionist epistemology who adopts a sociocultural framework in their work to then collect quantitative survey data on individual student’s performance on a task and analyze it for frequency counts. These types of dimensional mismatch are opportunities for individual researchers and our field to consider the underlying assumptions in our work.

6. Conclusion

What have we gained from constructing and populating a map of PER based on dimensions common in general education research? For individual researchers, we hope they have gained insight into how their work relates to other work in the field. In doing so, it might allow them to identify new avenues for their research trajectories that are consistent with their fundamental commitments (for example, to epistemologies, contexts, or theoretical frameworks) but stretch them in new ways. Additionally, we hope the map provides multiple entry points into the general education literature. For example, once Tor identified his theoretical commitment to a dynamic model of individual cognition, he was able to select papers to read from the subset of mathematics and science education that adopt a similar framework. The broader field of education research becomes more tractable when individual researchers know where they fall along these dimensions.

These dimensions can also help individual scholars identify intellectually meaningful points of divergence from others in the field. If we do not purposefully identify and acknowledge those divisions (which surely and appropriately exist!), we may default to creating ad hoc divisions based on stereotypes or caricatures of another scholar’s work. For example, rather than characterizing Rosemary’s work as just an example of the “Maryland tradition,” someone could use the map to highlight dimensions along
which her work varies from others within that tradition,\textsuperscript{225} and is continuous with work from other traditions.\textsuperscript{210} In that way, the map might push us beyond thinking about homogenous “camps” within the field, moving us intentionally away from potentially toxic assumptions about the work undertaken by scholars in other research groups.

For the field, these seven dimensions are spaces where scholars can begin to be transparent about their work so that we as a field can identify where we are. As such, we hope this map provides us with an opportunity to pause and study whether we are populating the map in the way that allows us to reach our goals. For example, we are now in a position to ask ourselves: Have we selected appropriate portions of each dimension that will allow us to assess our success in improving undergraduate instruction for all of students? Or are we clustered in some portions of the map? And if so, why are we clustered there?

In addition to assessing where we are, we also hope this map can be a starting point for developing a systematic plan for growth and expansion in the future. There is no doubt that PER will continue to grow in the coming years. New scholars are constantly joining the field, and we are excited to have their voices and perspectives as we work together to make sense of physics education. If we truly hope to achieve a deep understanding of the dynamics of physics teaching and learning, we must be intentional about our research directions along each of these dimensions. Though we have attempted (from our privileged position) to draw attention to the work of the remarkable scholars in our field who are pushing us along each of these dimensions, we know that we have not captured all the innovative work in our field. We wish to use this work as an emphatic and unequivocal call to each of us to elevate the voices of these scholars, so that we as a field can recognize their efforts and follow their lead. It is only when we come together to discuss our existing multidimensionality that we can make informed decisions on how PER can and should proceed with its important work.

References


Russ and Odden, *PER as a Multidimensional Space*


