Student representations of a community of practice

W. Brian Lane[*] and Cortney Headley
Department of Physics, University of North Florida, 1 UNF Drive, Jacksonville, Florida 32224, USA

(Received 13 December 2021; accepted 25 July 2022; published 16 August 2022)

The communities of practice (COP) framework is useful in understanding the effort to expand physics education into professional preparation. This framework prompts physics educators and physics education researchers to consider "what counts as doing physics" that we want to prepare students for and how we can model professional physics practice in our classrooms. We argue that this focus on community omits an important consideration of the student's perceptions of the physics community, which informs how they navigate the community. We introduce the idea of a COP model to describe a student's internal representation of the community's goals and practices and their sense of membership within the community. The student develops their COP model in response to legitimate peripheral participation within the community and uses this model to extrapolate their experience of the local community to the global community. We describe how this construct shares similarities with other frameworks but retains distinct features that make it a helpful tool for analysis. We demonstrate the use of the COP model in the review of student interviews about the use of computational practices in the physics community. The COP model helps us interpret student responses in terms of their COP models' alignment and misalignment with the physics community. We discuss implications for instruction and reflect on the utility of the COP-model construct.

DOI: 10.1103/PhysRevPhysEducRes.18.020110

I. INTRODUCTION

Physics education is being reformulated from imparting technical knowledge to future academics into training future professionals bound for diverse careers [1]. This evolution expands the focus of physics education to include practices that are useful in physics, science, technology, engineering, math (STEM), and beyond. One way of expressing this perspective is the communities of practice (COP) framework [2–4], which frames learning as a process of the learner integrating into a community organized around agreed-upon goals and practices. Within this perspective, every physics class, research group, or student club is a local expression of the physics community and an opportunity for newcomers to navigate toward the center of that community.

We present in this paper a means of complementing this perspective of the community of physics with a consideration of how the learner represents that community as they navigate their place within it. By introducing a construct that describes students' mental models of a community of practice (COP model), we can compare the community of practice as it exists in reality with the students' perceptions of that reality. We use the COP model to explain trends we observe in interviews about how students adopt computational practices along their trajectories as physicists.

In Sec. II, we review essential features of the COP framework and how they inform a holistic approach to physics education. In Sec. III, we describe our new COP-model construct, outline how this construct further extends this holistic approach, and compare it with similar features from other frameworks. In Sec. IV, we outline the context and methods of an interview study that demonstrates the use of our COP-model construct, and in Sec. V, we present three themes from our interviews that are most appropriately explained by comparing students' COP models to the physics community of practice. Finally, in Sec. VI we discuss our use of the COP-model construct and outline implications for instruction.

II. THE COMMUNITIES OF PRACTICE FRAMEWORK IN PHYSICS EDUCATION

In this section, we review how the communities of practice framework helps us understand how students develop as physicists. We survey samples of PER work that has been conducted within this framework and demonstrate how this framework can inform teaching practices. We conclude by describing an aspect of the student experience that motivates our new construct in Sec. III.

[*]Brian.Lane@unf.edu

A. Elements of the communities of practice framework

The COP framework emphasizes how novices navigate their place within an existing professional culture by familiarizing themselves with that culture's common goals and conventional practices that fulfill those goals [2–4]. These goals and practices are collectively referred to as the COP's *sense of joint enterprise*. Based on Ref. [5], Quan, Turpen, and Elby define a practice in the scientific context as "a set of activities that are embedded within and work toward the aims of a scientific community" [6]. They elaborate that the practices within a scientific COP must be meaningfully connected with each other and used with the purpose of helping to meet the community's goal. Irving and Sayre describe these practices as "what counts" as doing physics [7].

By adopting the joint enterprise of a COP, a novice member of the community begins structuring their *lived identity* [2,6,8,9], which the COP framework defines as "a complex interplay between identity as a negotiated experience of self, a sense of membership, a learning trajectory, a nexus of multimembership, and a belonging defined globally but experienced locally" [10]. This identity is connected with demonstrations of competence in the practices that the COP values [10] and embodies what the novice comes to believe that it means to be a practicing member of the COP [11]. For example, when an undergraduate physics major engages in outreach, they can begin to view themselves as an intermediary between experts closer to the center of the community (their instructors) and novices even further out in the periphery (the outreach audience) [12,13]. Doing so prompts them to negotiate their sense of membership in the community ("I am more central to physics than the audience is.") and assess their learning trajectory ("I am headed towards becoming more like my instructors.") based on their competence in physics practices as demonstrated during the outreach activities ("People learned something from that demo I performed.").

A novice's navigation of a COP is envisioned as moving along a trajectory [6]. Wenger conceived of several possible trajectories, as illustrated in Fig. 1: insider trajectories (remaining central), peripheral trajectories (accessing the community without becoming a full member), inbound trajectories (peripheral-to-central), boundary trajectories (between two or more COPs), and outbound trajectories (exiting the COP) [2]. For example, in the context of physics education, an insider trajectory might be a physics professor leading a research group. A peripheral trajectory might be a pre-med student taking their required introductory physics courses in preparation for the MCAT. An inbound trajectory might be a junior physics major applying to physics graduate programs. A boundary trajectory might be an undergraduate double-majoring in physics and communication with the goal of becoming a science-focused journalist. An outbound trajectory might be an undergraduate changing majors from physics to mathematics.

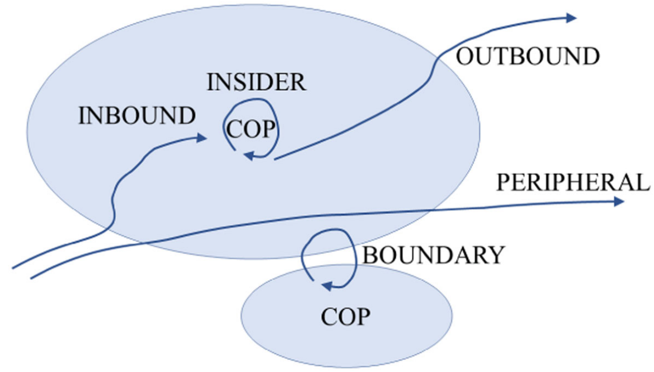

FIG. 1. Wenger conceived of several possible trajectories a learner might take in relation to a community of practice: insider trajectories (remaining central), peripheral trajectories (accessing the community without becoming a full member), inbound trajectories (peripheral-to-central), boundary trajectories (between two or more COPs), and outbound trajectories (exiting the COP) [2].

The population of junior physics majors we consider in Sec. V leads us to focus this discussion on inbound trajectories, but we recognize that the full suite of trajectories helps one understand a diversity of student experiences.

Movement along an inbound trajectory "is neither a linear nor smooth process" [6], and is exhibited by the learner's adoption of the COP's goals and approaches, and their increasingly central and significant role within the community [14]. In moving along this trajectory, the learner's membership within the COP "shap[es] their perceptions, values, and interactions with others" [8], and each step along an inbound trajectory is paved with the appropriation of a new practice [10,15,16]. A possible assessment of a learner's trajectory could be their appropriation or rejection of the community's practices and norms as embodied by central members [10,17–19].

We emphasize that, as each learner approaches a COP along an inbound trajectory, their trajectory is as unique as their background, culture, and personal identity. Making an analogy with spherical coordinates, while all inbound trajectories are characterized by $|\vec{r}| \to 0$ (with the center of the community at the origin), each trajectory can have a unique set of angular values (θ, ϕ) over time. If central members of the community tend to favor inbound trajectories that fall within a subset of angular values (for example, newcomers who enter the same way the existing central members did), their community's membership will not represent the makeup of the surrounding world.

Many learners will find themselves navigating multiple COPs concurrently, which Wenger called a *nexus of multimembership* [2,8]. For example, a student pursuing a career teaching high school physics must navigate the COPs presented by their physics coursework, their education coursework, and the school in which they intern. It is similarly important to consider smaller COPs within a broader COP, such as distinguishing the condensed matter COP from the elementary particle COP within the broader physics community. One can even bifurcate down to an individual class or research group as a COP which serves as a local picture of the global physics community [7].

As part of this navigation, the COP's sense of joint enterprise is constantly being renegotiated by its members, particularly as newer members move from peripheral positions to more central positions [10]. For example, a research group's focus or methods might change, or the set of problems that hold a subfield's interest might expand into new territory or migrate away from topics that have been sufficiently explored. We might say that the very existence of physics education research (PER) as a subfield of physics research is indicative of the expansion of the goals and approaches of the broader physics COP. The nexus of multimembership is particularly important for this renegotiation, so that new ideas can be applied to a community's existing purposes. For example, the introduction of computation to physics education (which we discuss in greater detail in Sec. IV A) is a renegotiation of the community's practices based on developments in the technology community [20–22].

B. Communities of practice in physics education

The COP framework is helpful in reframing the mission of physics education with an eye toward diverse 21st century careers [1]. In the language of the COP framework, an important overarching goal of the physics curriculum is for students to begin to align with the goals and approaches valued by the physics (and, more broadly, STEM) community through *legitimate peripheral participation*: "participation in practices in which a learner can engage that are socially warranted or legitimized by existing practitioners… and are appropriate for a newcomer" [10], leading the newcomer to pursue an inbound trajectory [23]. In this participation, students (ideally) develop their confidence in their ability to contribute to the community's goals using the community's practices. The student's learning is thus an adoption of shared understanding and practices [4,10,24]. This participation takes place in the local community context ("What practices are important in this department, this course, or this research group?") as an expression of the global physics community ("What practices are important in a given research field, as expressed in community artifacts like research papers and conference presentations?").

This overarching goal is an example of one's lived identity as being defined globally (by the broader physics community) but experienced locally (within a particular course, curriculum, or research group). The local context, as a microcosm of the broader community, provides well-defined local engagement in the practices that are meaningful within the global COP [10].

The importance of the learning environment (in the classroom, a department, a curriculum) cannot be overstated in regards to helping students progress along their appropriate trajectories, particularly along an inbound trajectory that retains a student within the physics COP. For example, participation in undergraduate research (a key event in the physics learning experience) plays an important role in undergraduates' trajectories toward becoming practicing physicists [25]. The availability of legitimate practices enables them to explore possible trajectories [16,23]. For example, structural choices in a practice-oriented physics laboratory course can help establish the course as a local COP, motivate student engagement with that local COP, and establish students on inbound trajectories [7]. A learning assistant program [26] can develop into a COP [8], with the learning assistants and associated faculty developing their own practices for feedback [27]. Similarly, a physics student can develop their identity as a subject-matter expert through informal outreach to learners of varying backgrounds [13], providing a demonstration of their increasingly central membership in the physics community [12]. Finally, the COP framework can be used to understand the experiences of underrepresented groups [28–30], as the lived identity developed in a COP is an important factor in student persistence in physics [7]. Understanding and appreciating the breadth of possible student trajectories within our local and global physics communities is necessary for supporting students from underrepresented groups. We next consider how students perceive the physics COP as they navigate these trajectories.

C. The underexplored student perspective

One topic that remains underexplored in PER is how students conceive of the physics community of practice. For example, when a new undergraduate student considers whether to major in physics, what perceptions about the community of physicists guide their decision? Or when a student says they want to major in physics, what do they think they're signing up for? Much work has been dedicated to students' perceptions of and attitudes toward physics as a subject, but not about their considerations of physics as a world in which they might participate.

This perspective is important, as a misalignment between experts' practices and students' perceptions can hinder students' progress along an inbound trajectory. For example, consider the student who perceives physics as a field that "has the exact answer to everything." We could certainly understand (perhaps even identify with) this perception, given how high school and first-year undergraduate physics courses focus on problems with exact analytical solutions. A student who finds this appealing could conceive of physics as consisting entirely of such solutions. When this student reaches, say, their second semester of upper division quantum mechanics, they might be shocked at the number of approximations employed to study (not solve) an analytically intractable problem. Such a misalignment between the student's *internal* *representation* of the physics community's practices and the community's *actual* practices is not well described by the COP framework. In the next section, we propose a new construct to expand the considerations of this framework.

III. STUDENT MENTAL MODELS OF THE PHYSICS COMMUNITY OF PRACTICE

In this section, we discuss the need to attend to students' mental models of the COP they are navigating, particularly in the context of the physics COP. After introducing terminology from the mental models framework, we explore how a student's mental model guides them as they navigate a COP, and discuss how these models are important to the student experience.

A. Mental models

The mental models framework describes how learners use internal representations to guide their reasoning and form expectations based on experiences [31]. Mental models are "abstract representations that store the spatial, physical, and conceptual features of experiences" [32], or "systematically constructed representations of physical systems, used to describe, represent, and explain the mechanisms underlying physical phenomenon" [33]. Mental models are built out of predictions and explanations for the reality they imitate [34,35]. Learners use mental models to facilitate "retrieval in the service of problem solving, inference generation and decision making" [32] and to "ground abstract scientific ideas" [34] that they can then analyze mentally and create new inferences and associations [36].

The formation of mental models lies at the heart of much of the learning process. Mental models are formed from the learner's experiences [34,35], and, as such, mental models are unique across individuals and dynamic over time [37]. Model-based learning can be understood to start with learners' preexisting models (preconceptions) and designed to reach a target model (learning objectives) at the end of a series of intermediate models (partial understanding) [38]. Louca *et al.* consider mental models to have five elements [33]: (1) physical objects, (2) physical entities, (3) object behaviors, (4) interactions among objects, entities, and behaviors, and (5) accuracy of the model's descriptions.

B. The COP model: A map for career navigation

We suggest that an important factor in a learner's pursuit of any STEM career (not just physics) is their *mental model of the community of practice* (which we call a COP model) relevant to that career. Attending to these models is important, as students' dispositions toward STEM are heavily influenced by the professional and personal authenticity of their STEM learning experiences [39–42], and these dispositions influence the type of trajectory a student pursues within a STEM community, thereby impacting representation within the STEM community. In the classroom context, a student's inbound trajectory begins with authentic learning experiences that promote a COP model that aligns with the global COP as it exists in reality. We illustrate our construct of the COP model in Fig. 2, which we unpack throughout this section.

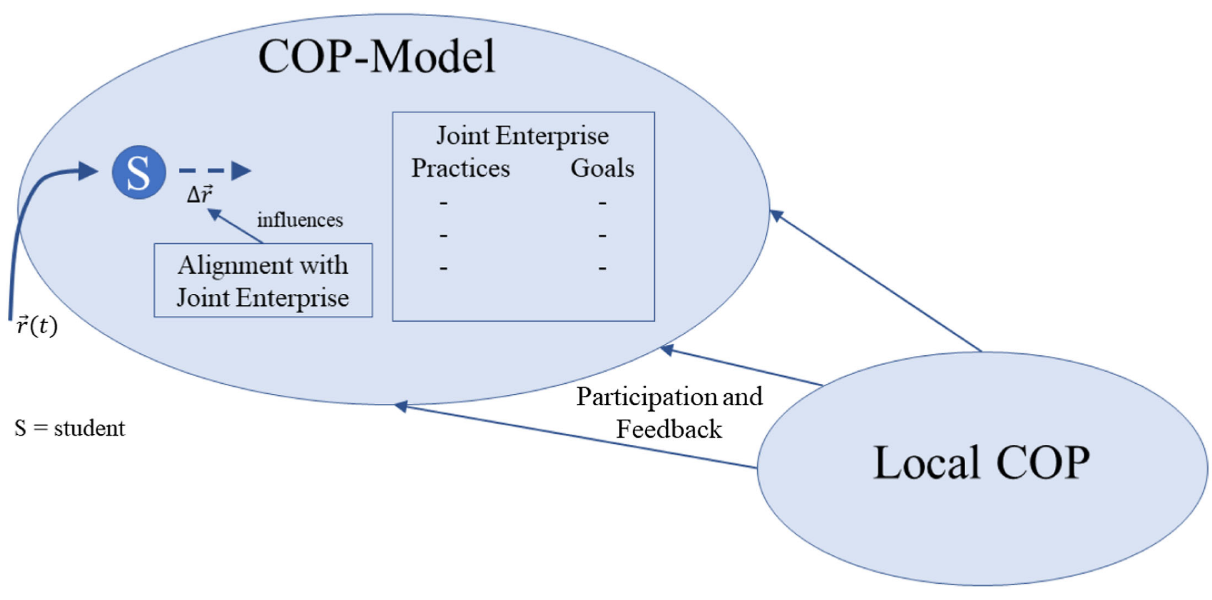

FIG. 2. The construct of a COP model. The student's mental model includes their trajectory history [$\vec{r}(t)$], their next step ($\Delta\vec{r}$), and their understanding of the community's sense of joint enterprise. Their next step is informed by their current sense of alignment with the sense of joint enterprise. All these elements are shaped by the legitimate peripheral participation in the local COP. We apply this construct specifically to the use of computation in physics education, but believe it can offer insights into all STEM communities.

In a COP model, the system being represented is the global professional COP that a learner is navigating as a new member based on their interactions with their local academic COP. Using Louca *et al.*'s list of elements [33], we identify this mental model as consisting of the following:

1. *Objects*: individuals and institutions such as practitioners and departments. This set of objects includes the learner, other members of the local academic community (such as classmates and professors), and members of the global professional community (such as conference presenters or published authors).
2. *Entities*: qualities of those individuals and institutions that describe their membership within the community. These qualities include the learner's expectations of participating in the COP, confidence, position, and trajectory.
3. *Behaviors*: actions and practices that the individuals and institutions engage in. This set of behaviors includes the learner's legitimate peripheral participation and examples they observe carried out by central community members.
4. *Interactions*: the sense of joint enterprise that guides the individuals and institutions, establishes standards for qualities, and mediates actions and practices.
5. *Accuracy*: the alignment between the learner's COP model and the COP in reality.

We further describe a COP model as follows.

1. A learner's COP model includes the goals and practices that make up their understanding of the COP's sense of joint enterprise

The COP's sense of joint enterprise is represented as interactions among the model's objects, entities, and behaviors. This representation (a list of goals and practices in Fig. 2) helps the learner answer questions like, "What common goals guide individuals and institutions to perform certain practices?" or, "What go-to practices do members of this community use to reach their common goals?" or, "What counts as doing physics?" We emphasized earlier that inbound trajectories are characterized by the novice's adoption of the COP's goals and practices [10,14–16]. We now emphasize that, before a novice can adopt those goals and practices, they must be represented in the novice's mental model of the COP. Conversely, a novice will not adopt a goal or practice they do not first see in their COP model. As mentioned earlier, the novice's perceptions and values (such as their personal answer to the question, what counts as doing physics?) must be shaped to align with the COP in reality [7,8]; these perceptions and values are held in the novice's COP model.

A newcomer to a COP is likely unfamiliar with these goals and practices and has no representation (or a misaligned representation), while an established member near the COP's center is likely to have a well-aligned representation of these goals and practices. Many physics educators observe this phenomenon anecdotally in introductory mechanics courses when students think that practicing physicists spend their time solving free-body diagrams or studying the motion of projectiles. Such a mental representation of the physics community's sense of joint enterprise lacks extrapolation to more modern topics and practices.

We see the COP model as what Irving, McPadden, and Caballero are referring to when they write that the identity that a learner develops in the local academic COP "give[s] the participant a sense of how their practices and participation fit within a broader context" [10].

2. A learner's COP model includes their sense of membership within the COP

When studying students' participation in informal physics outreach, Fracchiolla, Prefontaine, and Hinko employed an operationalized communities of practice framework that "allows us to sense where the university students see themselves within the community of practice and to learn what aspects of that community impact their involvement" [12]. Similarly, we see the COP model as a map that guides the learner along their trajectory [$\vec{r}(t)$ and $\Delta\vec{r}$ in Fig. 2] within the COP. This perceived position and trajectory are informed by the learner's confidence in their ability to contribute to the COP's goals using the COP's practices. This sense of position helps them answer the questions, "Where do I fit in this community?" and, "What does this community think of me?" [43]. For novices on an inbound trajectory, increased confidence scales inversely with their perceived distance $|\vec{r}(t)|$ from the center of the COP. This spatial element depicts the relative position of the learner within the community, and the learner's next step along their trajectory.

A learner's perceived trajectory gives them an indication of their progress toward or away from the center of a COP. This perceived trajectory helps the learner negotiate their experience of self in comparison to the COP and answer the question, "To what degree is this community's joint enterprise *my* enterprise?" These considerations inform the learner's trajectory (continuing toward the center or periphery, changing direction, changing speed) and career decisions (the degree to which their future career is connected to this community). This sense of progress is informed by their sense of how the COP's goals align with their own interests [44] and how the COP's practices align with their own competencies. We expect that an inbound trajectory is accompanied by an increasing sense of alignment with the COP.

3. A learner develops their COP model in response to legitimate peripheral participation and feedback

Mental models are built from experiences, usually in an attempt to make the model better align with reality and thereby improve its usefulness as a reasoning guide.

A student progressively builds their COP model from legitimate peripheral participation [10,17,45] and the resulting feedback (arrows between the two ellipses in Fig. 2). As noted earlier, "Identity as membership in a COP connects identity with forms of competence" [10]. The learner's interactions with the local COP develop and demonstrate the learner's competencies with the COP's practices through requirements (what the community expects) and resolution (the community's evaluation). Similarly, legitimate peripheral participation guides novices in appropriating the practices of the community as they move along an inbound trajectory [10,15,16].

The COP's culture, goals, and approaches determine the nature and expectations of legitimate peripheral participation, such that this participation refines the sense of joint enterprise represented in their COP model (list of goals and practices in Fig. 2). In the learner's COP model, the competencies that legitimate peripheral participation demonstrates are qualities (entities) that describe the learner (an object) and help evaluate their alignment with the COP (their "understanding of self within [the] community" [10]) and identify their position and trajectory. From this perspective, one goal of legitimate peripheral participation is for learners to develop a COP model that is aligned enough with reality to guide their interactions with the COP and form expectations as they navigate the COP.

Misalignment between students' COP models and the corresponding COP in reality has been observed in STEM education research. For example, Franz-Odendaal *et al.* found that "Grade 7 students do not grasp the importance of science/math requirements for future STEM careers" [45]. "Grasping the importance" of competencies expected in a career is not a matter of understanding or even developing those competencies, but perceiving them as a valuable requisite of one's career goals. This sense of value is represented in the students' COP models.

Similarly, in the context of information technology, Agosto, Gasson, and Atwood argue that one reason female students divert from IT careers is that they do not perceive that an IT career can overlap with their goal of solving problems [46]. In the broader context of STEM, Diekman *et al.* argue that women opt out of STEM careers because they see STEM fields at odds with fulfilling their communal goals [47]. These expectations are misaligned from how IT professionals would describe problem solving as a key element of their jobs and how STEM professionals would describe their careers as fulfilling communal goals. Helping female students incorporate this "goal congruity" [44] into their COP models is an important goal in reforming STEM education.

4. A learner's COP model enables them to extrapolate their experience of a local COP to an understanding of the global COP

We see this purpose as especially salient for undergraduate students, whose experience of the COP in reality is limited to the context of their local COP within an academic program or research group. They must extrapolate this experience to a model of the global professional COP [6].

As a fictional analogy, consider the 2005 film *Robots*. The protagonist, Robbie, has grown up dreaming of a life in Robot City, working for Bigweld Industries, where he believes he will be welcomed to bring new ideas, receive support in actualizing those ideas, and contribute to the betterment of robot society. This is Robbie's model of the Bigweld Industries community of practice, which he developed from representations of the company portrayed on television during his childhood. About halfway through the movie, Robbie discovers that the company has been taken over by new leadership that has changed the community into a hostile and classist environment, not even allowing him to enter the company grounds. The community's sense of joint enterprise has changed, causing severe cognitive dissonance for Robbie. On a phone call with his father back home, he despondently relays, "It's not like we thought." The COP in reality, he has discovered, is drastically different than his COP model.

5. Comparing models of different COPs helps a learner develop and negotiate their nexus of multimembership

No student is a member of the physics community only, a principle which Wenger refers to as a nexus of multimembership [2]. The models a physics student develops of the various communities to which they belong (family, neighborhood, academic, athletic, professional, religious, etc.) helps them understand how these communities intersect and support each other or stand disparately from each other. These mental models allow the learner to easily juxtapose their communities' goals and practices, compare their sense of membership within each community, and negotiate their responsibilities toward each community. Such comparison might play a crucial role in the learner's decision of whether to persist along an inbound trajectory in a given community ("Is this new community compatible with my existing communities?"), a process which has direct impacts on the community's representation ("Why is no one from that community centrally involved in this community?") [44,47–49]. From this perspective, representation becomes a result of communities comfortably sharing central members based on the development of compatible COP models. Once multimembership is established, the interplay between models of different communities enables the shared member to transfer ideas from one community to another, helping to develop the sense of joint enterprise.

Having described the COP-model construct, we conclude this section with a comparison of COP models with other similar but distinct frameworks and a brief discussion of how COP models can be useful in the classroom context.

C. Comparison with other frameworks

While the COP-model construct is a novel introduction to the communities of practice framework, it must also offer distinct insights compared with other frameworks in order to prove sufficiently useful. The COP model has many features in common with *figured worlds*, *possible future selves*, and *social cognitive career theory*. Here, we briefly summarize how these frameworks are similar to but still distinct from the COP model.

1. Figured worlds

The figured worlds framework focuses on identity as "how people come to understand themselves, how they come to 'figure' who they are, through the 'worlds' that they participate in" [50]. The "worlds" in this case are "socially produced, culturally constituted activities" [51] where people conceptually and materially produce new identities as expressions of the normative values upheld by the figured world [52]. A figured world is characterized by a recruitment or entry process for novices to enter the figured world, a context of meaning to grant significance to social encounters and people's positions, and social organization into which people are sorted [51]. The actions that constitute a figured world are largely relational (how people interact with each other in that world), such that the figured world exists in a community whose actions create the figured world [50]. Participating in the figured world is reciprocated by recognition that "you're one of us" [52].

These concepts sound very similar to the Communities of Practice framework, particularly with our COP-model construct adding an internalized dimension that helps describe the individual's navigation within the community of practice along a trajectory of identity. These similarities can be seen in the literature. For example, when working within the figured worlds framework to describe an interdisciplinary STEM learning environment, Kapon, Schvartzer, and Peer seem to borrow the term "legitimate participation" from Communities of Practice (perhaps inadvertently, as they make no explicit discussion of Communities of Practice) [53]. Their definition of "legitimate" ("valued in the figured world") is reminiscent of the sense of joint enterprise. Sisson *et al.* use the concept of communing [54] to describe the process of forming and reforming figured worlds, similar to how the sense of joint enterprise can be renegotiated [10].

A full comparison of communities of practice and figured worlds is beyond the scope of this paper. However, we identify three key differences that maintain a distinction between the COP model and a figured world. First, the communities of practice framework (and therefore the internal representation of the COP model) is focused on goals and practices while figured worlds is focused on qualities and dispositions of the individual whose identity is being formed. For example, Danielsson *et al.* [52] examined the figured world of a university quantum mechanics classroom, which includes the quality of what it means to "be a good student" in such a classroom. One manifestation of this quality is "finding quantum mechanics 'weird'." Such a disposition is not traditionally thought of when describing a community of practice. A figured world answers the question, "What are we like here?" while a COP model answers the question, "What are we hoping to accomplish here, and how?"

Second, the COP model is an internal representation a member refines and references, while a figured world is shared with others with the goal of helping them construct their identity in relation to this world [52]. Based on this contrast, we see a figured world as one or more central members' expression of their COP models, a statement of, "Here is what our community is like, based on my internal representation." Conversely, the peripheral member's COP model is developed by the figured world they experience: "Here is what I have learned about this community based on the figured world this central member created." In this sense, the COP model is a bridge between these two frameworks.

Finally, the figured world's framework focuses on "how individuals can author themselves in a social space" based on social norms and expectations, while communities of practice focuses on "the sociocultural space" where these norms and expectations are defined [55]. So, the COP model is an intermediate feature which the novice uses to internally represent those norms and expectations. In other words, while a figured world helps the learner develop their identity in response to norms and expectations, the COP model helps the learner identify whether they are interested in forming their identity around those normative values.

2. Possible future selves

The possible future selves framework [56] considers "people's concepts of who they might become, who they would like to become, and who they are afraid of becoming in the future" [57]. In this framework, a possible future self is a representation generated from experiences that helps a person imagine themselves in the future [58]. The consideration of these possible selves is an important factor in career decision making [59] and motivating students' persistence [60], and this framework is helpful in explaining the gender gap in STEM career pursuits [61].

The idea of a possible future self holds similarities to our COP model: Each is an internal representation developed in response to socially situated experiences that help a student make career decisions. However, we note that while the possible future self represents the self in the future, the COP model represents a community in the present. These representations help the student address distinct questions. A possible future self can help the student answer, "Can people like me graduate from college with a physics degree?" [60], while a COP model helps them answer the questions, "What do people do once they have a physics degree? What is the world of physics like?" These questions are clearly related, and students develop answers to them concurrently, but the difference in subject (the self versus the community) highlights the different focus of the two frameworks.

The COP model, once further explored, can be seen as generative fodder for possible future selves. Learners use the COP-model representation to imagine possible future selves, but the representation is first developed in the context of a community of practice. Therefore, we situate this construct within the communities of practice framework, although it holds relevance for possible future selves.

3. Social cognitive career theory

Finally, social cognitive career theory (SCCT) posits that novices develop their curiosity, interests, and aspirations in a career through a series of performance accomplishments that promote confidence and outcome expectations [62,63]. Here, confidence is the student's answer to the self-assessment, "Can I accomplish this task?" Outcome expectations are the student's understanding of, "What will happen if I accomplish this task?" A performance accomplishment is a task that a learner completes with the anticipated result that a success will tend to raise their confidence and outcome expectations and a failure will tend to lower their confidence and outcome expectations.

Performance accomplishments are similar to legitimate peripheral participation, in that they both help one navigate toward the COP's center and refine the learner's interests in moving toward the center [10,11]. Additionally, central COP members formulate and assess performance accomplishments for peripheral members based on their COP models with the implicit goal of refining the peripheral member's COP model. We think this similarity reveals an important link to our COP model, in that a performance accomplishment is an interaction between the learner and the COP that shapes the learner's COP model. Conversely, we think that the COP model helps inform the learner's interpretation of a performance accomplishment and the resulting feedback [62].

One shortcoming frequently highlighted within SCCT is how it frames career choice as a construct that becomes essentially static in one's early career [62], a notion that is certainly challenged today with professionals' frequent changes in career [64,65]. We believe that the COP-model construct helps expand the considerations of SCCT by describing an individual's life-long decisions about their trajectory within a professional community. We see these decisions as based on the individual's understanding of the community's sense of joint enterprise (internalized list of practices and goals in Fig. 2). The COP model also emphasizes that novices choose a career based on their perceptions of how the COP's goals align with their own interests (outcome expectations) and how the COP's practices align with their own competencies (confidence). Such perceptions do not necessarily match the actual overlap between a novice's COP model and the COP that exists in reality, such as in the case of impostor syndrome [66–68].

We think that SCCT holds the most fruitful overlap with our COP-model construct, and plan to explore this overlap in the future.

D. COP models in the classroom

It is important that educators attend to how well a student's COP model reflects reality, since (i) a student who professes interest in a STEM career but has unrealistic expectations of that career is unlikely to persist [69] and (ii) a student who declines to pursue a STEM field but whose COP model does not include appealing facets of that field is missing out on a potentially rewarding career and might unnecessarily opt out of the field's employment pool [70]. The formation of students' COP models is part of the teacher's role as a "broker," shaping their local academic community to better match the global professional community [7]. We argue that educators would do well to attend to the development of students' COP models as part of the scaffolding process in a course, such that students can begin to chart their own inbound trajectories rather than following the trajectories explicitly laid out by their instructors and mentors [69]. Such attention is likely to affirm a greater diversity of student trajectories into the STEM community and thereby support representation within that community.

In particular, we believe this construct helps to inform several important learning objectives:

- Students will formulate reasonable career goals in relation to STEM interests and expectations.
- Students will develop a positive perception of themselves and their classmates as "STEM people" [71].
- Students will practice activities relevant to STEM professions.

Additionally, it is important for educators to reflect on their own COP models. Are we presenting physics in our classrooms as it exists in reality? And are we representing to students authentic expectations of what it's like to navigate the physics community? We will see an example of such reflection in Sec. V C.

Finally, students' COP models can impact persistence and diversity within physics professions, since "What type of people are included in the physics community?" and "Do others see me as a physicist?" are addressed in a student's COP model [71,72]. Educators and mentors might be able to proactively develop learners' COP models using metacognitive tools demonstrated to help students develop and use mental models [37].

We think the construct of a COP model warrants further investigation, and that it could be used to design assessments and interventions to help educators more directly develop students' perceptions of physics as a professional community. We illustrate the use of the COP model in helping us understand a set of student interviews about the use of computation in the physics community.

IV. CONTEXT AND METHODOLOGY

We used the COP-model construct to help us understand student interviews about their experience learning computation for the first time in upper-level physics courses. In this section, we briefly review the state of computationally integrated physics education and some insights from research into this practice. Then, we establish the academic context for our study and define the COP we are considering. Then, we review the design of our study and some characteristics of our interview subjects. In Sec. V, we present the contents of our interviews that demonstrate the use of the COP model.

A. Computation in physics education

By "computation," we mean the use of a computer to help students learn physics. This use can include simulating physical systems, conducting advanced analysis of experimental data, creating insightful visualizations, exploring analytically intractable problems, and bridging the gap between mathematical problems and experimental activities [21,73–81]. Computationally integrated physics education also helps prepare students with practical skills relevant to industry and graduate study [20–22,80,82–87]. In the language of the COP framework, computation is considered a set of recognized practices that physics and STEM communities use in pursuing a variety of goals [80,82,84–89]. These are the scientific practices that form "a set of activities that are embedded within and work toward the aims of a scientific community" [6].

In terms of our COP-model construct, students do not always perceive computation as relevant to the goals of the physics community, or the broader STEM community. For example, Lunk and Beichner [90] described life science majors considering computation to not be "useful." Gavrin, Vemuri, and Maric observed a significant jump between the sophomore and junior year in students' describing computational methods as "equally necessary in the field of physics" with experiments and analytical solutions [91]. Hamerski *et al.* [92] observed students "intentionally separating" computation from physics. These students reasoned that, since they can learn physics without computation, computational activities are simply more hoops to jump through. We are obtaining more formal data about this phenomenon as part of a larger study that the present paper will help inform. In the language of our COP models construct, there is a misalignment between students' representations of how computation figures into the physics community and the actual role of computation in that community.

We illustrate this difference in Fig. 3 with two pie charts depicting possible representations of the practices employed by the physics community. The pie chart on the left depicts a representation a professional physicist is likely to adopt: The categories of experiment, theory, and computation occupy roughly equal prominence in the types of practices that the physics community uses (with each member of the community likely spending most of their time in one wedge). The pie chart on the right depicts a representation that many students seem to adopt: Physics practice is dominated by experiment and theory, with computation used by only a small fraction of the community.

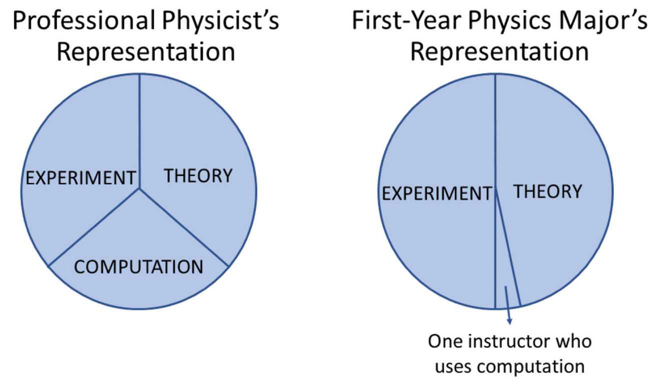

FIG. 3. Pie charts representing possible internal representations of the physics community's practices that a professional physicist (left) and first-year physics major (right) might adopt based on their differences in experience. A professional is likely to give comparable space to computation, experiment, and theory, while a first-year major might have limited experience with computation, leading to different expectations of the practices used by the physics community.

This misalignment between the community's practices and students' perceptions can hinder students' progress along an inbound trajectory. For example, consider the student who learns how to carry out numerical integration in a computationally integrated upper-division electromagnetic theory course. The student might use a numerical integration code to evaluate the electric potential or electric field for dozens of charge distributions. Now suppose the next semester begins and the student is enrolled in a quantum mechanics course where computation is not integrated. The student *could* use the numerical integration practices they learned in electricity and magnetism to evaluate the many integrals encountered in quantum mechanics, but only if the student perceives numerical integration as personally helpful and a valid approach in this new context. They need to transfer the usefulness of computation from the community of their electricity and magnetism class to the community of their quantum mechanics class, knowing that computation is valued in the global physics community. Such an extended application would be evidence of their progress along an inbound trajectory. If, instead, they relegate numerical integration to a course-specific requirement, they likely will not activate this knowledge [93–95] to use in the new context [96], stalling their progress along an inbound trajectory. Considering the COP framework can help address such transfer issues by maintaining the link between local academic activities and global professional practices [2,10].

To explore this misalignment between novice perceptions and professional physics practices, we conducted semistructured interviews of students who had recently encountered computation in their upper-division physics coursework. We use our COP-model construct to explain three key features in these interviews and answer the question: How can the COP-model construct help us understand students' adoption of a new practice?

B. Academic context and scope

We recruited students to these interviews from the physics program at a mid-sized primarily undergraduate regional state university. This program graduates 10–20 physics bachelors each year, emphasizes research opportunities for undergraduates, and has 9 tenure-track or tenured faculty, 5 nontenure track faculty, and 6 visiting full-time faculty. In fall 2020, three faculty members (including this paper's first author) integrated regularly occurring computational assignments into three upper-division physics courses (Astrophysics I, Mathematical Physics, and Modern Physics). These computational assignments were based on minimally working programs (MWPs) [97–100], which provide students with a sample code to develop rather than requiring students to begin writing code from scratch. This implementation of computation places this department among the 52% of departments in the USA reported to have at least 1 faculty member teaching computation in an advanced-level physics course, and the 39% of departments whose faculty use computational homework [101].

For the purposes of this paper, we define the COP of our study as the physics majors and instructors within a set of concurrent physics classes, which we view as a local representation of the global physics community [7,25]. We assume that the insights gained from this scope might be applicable to physics subdomains or to other subjects.

Because our student interviewees volunteered to participate, we are likely studying students who are more engaged in the process of learning physics than others in the population. Therefore, this report focuses on the utility of using the COP model in understanding student comments about computation, so that we can use the COP model to study more complete populations in the future.

We also note that this study involved a faculty member (the first author) interviewing students about their learning experience in his course. While the roles of educator and education researcher would ideally be separated, this compromise is a necessity in many "solo PER" environments. We do note that these interviews took place after this course concluded, and these students were not enrolled in any subsequent courses with the first author. Again, the goal of this study is to demonstrate the usefulness of the COP-model construct, and as such, drawing rigorous conclusions from the study is not as high of importance. With the COP model established, we can next develop means of assessing students' COP models with a higher degree of objectivity.

C. Study design and participants

We conducted semistructured interviews with these students in the spring 2021 semester, 2–3 months after they completed these computationally integrated courses. We designed this study as exploratory, obtaining descriptive data in a case-based structure designed to elucidate possible avenues for student learning [6,102]. We acknowledge that this timeline places the computationally integrated courses and the interviews in the midst of the COVID-19 pandemic. As such, the three courses featured split remote or on-site teaching formats, and the interviews took place over video conference.

These interviews serve as the primary source of information for us to conduct a case study of each student interviewed. A case study "investigates a contemporary phenomenon within its real life context, especially when the boundaries between phenomenon and context are not clearly evident" [103]. In our study, the contemporary phenomenon is the students' experience with learning computationally integrated physics in the context of a community of practice, making the boundaries between phenomenon and context unclear. Case studies are also appropriate when "a how or why question is being asked about a contemporary set of events over which the investigator has little or no control" [103]. Since our interviews took place after these courses concluded, we had no control over the events being discussed in the interviews. In a descriptive study such as ours, "the researcher has to make a speculation, on the basis of the literature and any other earlier evidence as to what they expect the findings of the research to be" [104]. Our proposition is that these students' experience of computation within this community of practice is best explained in terms of an internalization of the community of practice, our COP-model construct. Our unit of analysis is each student subject in the time frame of their fall 2020 course work and a few months immediately thereafter. This is a holistic, multiple-case design, as there is one unit of analysis (the individual student) and multiple cases (one for each student) [104]. We therefore seek to test the validity of our COP-model construct, "establishing correct operational measures for the concepts being studied" [104].

Students were recruited in January through March 2021 from the Fall 2020 class rosters, with interviews conducted in February through April 2021. Five students (with self-selected pseudonyms Chrissie, Guy, Harrison, Jose, and Paul) agreed to participate. Each student chose a pseudonym indicative of their gender. The one female student

TABLE I. Summary of student interview subjects.

	Physics enrollments			Programming background	
Student	Astrophysics I	Mathematical Physics	Modern Physics	Programming I	Programming II
Chrissie		✓	✓	✓	✓
Guy	✓	✓		✓	
Harrison		✓	✓	✓	
Jose		✓	✓		
Paul		✓	✓	✓	✓

interviewed (Chrissie) is also a member of an underrepresented minority. The students' course enrollments and prior experiences with programming are listed in Table I.

The student interview questions (Appendix A 2) were designed to prompt students to reflect on their computationally integrated courses chronologically, helping us understand their perspectives of their trajectories into the COP. We used Zoom video conferencing software to host, record, and transcribe these interviews. We shared responsibility for analyzing interview transcripts.

We sent student subjects a pre-interview survey to ask about their prior experiences with computation, confirm which computationally integrated physics courses they participated in, solicit their career goals, administer the Computational Thinking Attitudes Survey (CTAS) [105], and collect a pseudonym for them to be referred to during the interview. The CTAS assesses students' attitudes toward the use of computation in physics, and was included to complement their interviews.

The interviews followed a semistructured protocol [106] in which we outlined a set of general questions and established space for follow-up questions and clarifying statements based on the subjects' answers. The interview protocols and pre-interview survey are located in Appendix A 2.

We analyzed interview transcripts using the method of constant comparison [107], in which each author independently reviewed the transcripts to identify emergent themes that address our research questions. We revisited our theme definitions throughout the process and arrived at complete agreement on the theme instances within one round of discussion. These themes focused on difficulties the students described having with computation (such as getting started, their lack of experience, and retaining computational skills), their sense of confidence with computational tasks, and the purposes students assigned to computation (described in detail in Sec. V A). In Sec. V, we use the COP-model construct to explain these themes.

V. INTERVIEWS

In reviewing these interviews, we find three trends related to communities of practice that we believe are best explained in terms of COP models: The students' *goals* for using computation (representing partial alignment with the physics community), the students' *low confidence* in their use of the practices of computation (evaluated based on expectations that are misaligned with the physics community), and a *misaligned expectation* often expressed by central members of the physics community.

A. Partially aligned COP models seen in student goals for using computation

One aspect of a community of practice's sense of joint enterprise is the set of goals that the community exists to fulfill. An important aspect of navigating an inbound trajectory within a community of practice is adopting those goals. We see evidence of this development in the reasons our students discussed for using computation in a physics context. We explain this development as a partial alignment between the students' goals and the community's goals.

When asked interview question 1 ("When you picture a physicist conducting research, what kinds of activities do you imagine them doing?"), all five students included the use of computers in their answers. We recognize that the students knew this interview would focus on the use of computation in physics, but we did not previously mention computation in the interview questions. Therefore, this trend seems to indicate that these students' COP models of physics included computation at least to some degree after their computationally integrated course work concluded. In terms of Fig. 3, their internal representations of physics practice more closely match the balanced pie chart on the left. In terms of Fig. 2, computation holds a prominent place in the list of practices that represents the sense of joint enterprise.

Collectively, the five students identified various important benefits of using computation that overlap with the physics community's reasons for using computation as outlined in Sec. IV A. These benefits included visualization, efficiency, accuracy, data analysis, and sense making. We also saw that these students attributed personal importance to these benefits, as opposed to simply recounting their importance to the global physics community. For example, some students described how the efficiency afforded by computation helps them avoid burnout and focus on physical reasoning over mathematical derivations.

Looking at the interview excerpts overall, we note that most students prioritized one of these reasons above others in their comments. For example, Chrissie focused on computer visualization as a means of sense making, making comments like, “You can look at the graph and see, ‘Oh, so this goes towards this boundary or does it go towards this boundary’ … It’s different from just looking at the integrals involved… you don’t really know that means.” In contrast, Jose described how setting up the code itself was part of sense making: “You have to almost think about… the various concepts in different ways, so that you can put them into a program…” He gave an example of a computational assignment about radioactive decay that engaged him in different ways than his lab activity about the same topic. Meanwhile, Harrison described how computation’s efficiency was central to his sense-making process: “It’s one thing to say, ‘Okay, I see this in handwritten work that would take me three years to finish,’ but Python can do it in like 15 seconds… If computation wasn’t a thing, and I had to do this all by hand… I wouldn’t have the time.” We point out this contrast because, while central members of the physics community would agree that all three of these computational approaches to sense making are important, the students (presumably at the periphery) prioritize one over the others in their COP models.

As another example, Guy described computation as being useful for processing large datasets, an activity that was frequently highlighted in his Astrophysics I course. The other students did not mention large datasets, as this practice was not implemented in Mathematical Physics or Modern Physics. As Guy was the only student in our sample who took Astrophysics, his COP model holds this unique representation among the others.

Interestingly, Paul mentions efficiency, sense making, and visualization with roughly equal importance, and his interview answers and survey responses demonstrate one of the most positive outlooks toward computation overall. We suspect that this difference indicates that he has the most aligned COP model among these students.

We take these features to indicate that these students’ COP models are beginning to conform to the local COP in terms of the roles that computation plays in the physics community’s sense of joint enterprise. They all seem to have a unique position within the community [unique (θ, ϕ) as described in Sec. II] and their COP models generally motivate them to persist along an inbound trajectory. Supporting diverse valid trajectories in this way is an important aspect of holistic, learner-centered assessment, which we discuss further in Sec. VI B.

B. Misaligned COP models seen in students’ low confidence

The other half of a community of practice’s sense of joint enterprise is the set of practices that the community has agreed are appropriate to use in pursuit of the community’s goals. In these interviews, we find evidence that the practices represented in these students’ COP models are misaligned with the community’s practices.

We asked these students to reflect on their level of confidence in using computation in a physics context. Most of these students reported feeling unprepared to develop new code from scratch, and they attributed this lack of preparedness to the instructors’ reliance on MWPs. For example, Guy felt that, even after two computationally integrated courses, he was overly reliant on external sources: “If you told me to plot a dataset and show it with any kind of analyzing… the only way I could do it is to steal somebody’s code from, you know, messing around on Google… It doesn’t feel like I’m coding, it feels like I’m playing plagiarism.” In his COP model, Guy believes that professional coders would not use (“steal”) preexisting code from an internet search (“messing around on Google”) to solve a problem, but would start from a blank Python notebook. In contrast, searching for sample codes is exactly what expert programmers frequently do, rather than starting a program from scratch [84,86,87,97,99,108]. The prevalence of this practice is one of the main reasons instructors use MWPs [97–100]. In other words, Guy’s lack of confidence stems from failing to meet expectations that the physics COP does not actually hold.

Similarly, Jose seemed to think there were additional, more difficult, computational tasks waiting for him after these courses: “I imagine that computation is probably a wider field than I expect and that there’s some concepts that I’ll be further exposed to that will be more difficult.” His COP model includes a “wide field” of “more difficult” concepts that he has not encountered yet. We observed that these courses’ assignments are well aligned with practices within the physics community, so it is unclear what sorts of concepts might fit this description.

We take these differences as examples of how these students’ COP models do not fully align with the local academic COP (or, by extension, the global professional COP), as they expect to need skills not held as important by the COP. Still, the question of how the use of MWPs might undercut students’ confidence is worth considering further.

C. The community’s misaligned expectations of novices

We mentioned in Sec. III D the importance for educators to reflect on their own COP models, particularly in regards to what navigating the physics community as a learner looks like. Prompted by these interviews, we reflect on notions about the process of learning additional programming languages.

Many central members of the physics community work in multiple programming languages, so we understand that their COP models likely hold language acquisition as a recurring feature of an inbound trajectory. Computationally minded physics educators often express that learning a second programming language is an easier process than learning one's first programming language. Since they see how programming practices translate from one language to another, their COP model reduces this process to learning the syntax of how those practices are expressed in the new language. We make an analogy to music: Learning a musical instrument for the first time is challenging, as one must learn music concepts in addition to the particular expression of the instrument, while learning a second instrument requires only adapting one's conceptual knowledge to the new context. In terms of a COP model, this aspect of an inbound trajectory is seen as a straightforward process. This mental representation influences decisions made by computationally minded physics educators: For example, if subsequent languages are easier to learn, then the choice of language in one's physics course matters little, since students will be able to learn the next language they need with greater ease.

However, our interviews indicate that this representation of an inbound trajectory is misaligned with the reality experienced by these students. These students described their programming background as deficient even though most of them completed at least one programming course (see Table I). They described their struggles with learning a new programming language, especially with Python (the language used in their physics courses) functioning so differently than JavaScript or C++ (the languages used in their programming courses). We discuss this issue further in Sec. VI B.

VI. DISCUSSION

Having presented these three insights from our student interviews, we next review the limitations of our study, outline implications for computationally integrated physics instruction, and reflect on our use of the COP-model construct.

A. Limitations

Our interviews showed overall positive perceptions of computation, while the examples in Sec. IV A suggest a much more negative outlook. One important distinction is that many of the examples of negative perceptions come from the introductory context, while our interviews were confined to the upper-division context. Once we have a better understanding of these differences between students' COP models, we can better address how to motivate computation for our students.

As mentioned earlier, the self-selected nature of our set of student interviewees likely overrepresents students who are more engaged in the learning experience. However, we have observed that these students' experiences were not wholly positive, and can reasonably expect these negative experiences to be reflected in other members of the community. Similarly, the first author's role as a course instructor did not completely hamper their willingness to share negative experiences.

B. Implications for computationally integrated instruction

Based on the themes discussed in Sec. V and framed within our COP-model construct, we suggest the following implications for computationally integrated physics instruction:

First, we note the diversity displayed in how the students' COP models represent computation as a physics practice (Sec. V A). Each student's model prioritizes a different subset of benefits from using computation, which suggests that their success at a computational assessment might depend on the assessment's alignment with their COP model. For example, if each of these students were asked to complete a computational project that focused on producing a visualization, Jose and Paul might be more likely to engage with the project, while Guy and Harrison might feel disengaged, preferring to address more technical objectives. On the other hand, an assignment to optimize a code's performance would directly appeal to Harrison's interest but leave the other students uninterested. Such varying levels of engagement might lead to varying levels of performance, which could become coupled to issues of representation. Means and Stephens [42] argue that, when STEM instruction limits students' abilities to explore their interests, underrepresented groups can be adversely affected, since their interests are less likely to be represented in the instructional design. We therefore recommend that computational assessments leave room for students to explore and express their interests.

Second, we think it wise to examine the ways in which using MWPs might unintentionally undercut students' confidence with programming as observed in Sec. V B. Using MWPs certainly helps students meet the real expectations they will face in the professional COP, but we have observed that students' COP models can place a misaligned priority on developing code from scratch without internet searches. When instructors observe shortfalls in student confidence with programming, it would be worthwhile to investigate the expectations they are holding themselves to as represented in their COP models.

Finally, we recommend reexamining the frequently presented advice that learning a second programming language is universally straightforward. The rationale behind this proposition seems innocuous: When a student learns their first programming language, they must learn programming practices as well as the syntax of the language, while learning a second language requires only learning the new syntax. This is how many experts represent the process in their COP models. However, this representation goes against the experience reported by these students, who described in detail challenges they faced when switching from JavaScript or C++ to Python. The first author has begun a follow-up study to explore this process in greater depth. For now, we note that attending to this misalignment between the instructors' COP models and the students' experience will help improve student confidence.

C. Our use of the COP-model construct

In Sec. III, we outlined the COP model as a construct for understanding students' internal representation of a professional community of practice. The primary goal of our analysis is to establish the COP model as an appropriate framework for understanding these students' experiences. Here, we reflect on the role this construct played in our study and how these interviews lead us to affirm and revise the COP-model construct.

A learner's COP model includes the goals and practices that make up their understanding of the COP's sense of joint enterprise. This aspect of a COP model helped us design our interview questions to focus on students' experience using physics practices (such as building computational models and debugging) to achieve goals valued by the physics community (such as visualization and extracting insight). Identifying these practices and goals also helped us develop themes while reviewing interview transcripts. By considering how practices and goals are represented in a student's mental model, we distinguished between how practices and goals are established by central experts and how they are experienced by novices during legitimate peripheral participation. The trend of students' focusing on one or two goals for using computation prompts us to further consider what emphasis a student's COP model places on goals and practices. In the imagery of Fig. 2, we might say that the student's list representing the sense of joint enterprise has some items written in larger font, closer to the top of the list.

A learner's COP model includes their sense of membership within the COP. We envisioned the student's perceived position and trajectory as being informed by the degree to which the COP's goals align with their own interests and how the COP's practices align with their own confidence. We found these dimensions of interest and confidence to be useful metrics in understanding our students' COP models. We also observed that the students' confidence can be confounded when their COP model includes expectations that are not held in reality (in this case, coding from scratch without internet searches). In such a case, the student's perceived distance from the center might be greater than their distance in reality. In this way, the COP model can be used to represent and explore impostor syndrome [66–68].

A learner develops their COP model in response to legitimate peripheral participation and feedback. This aspect of the COP model prompted us to order our interview questions chronologically: We started with their Fall 2020 computational experiences and progressed to their present opportunities to use computation, and concluded with their expectations of using computation in the future. Doing so allowed us to trace the impact of the students' prior participation to the current outlook offered by their COP models. A logical next step is to trace changes in a student's COP model over time in response to their ongoing experiences in the community.

A learner's COP model enables them to extrapolate their experience of a local COP to an understanding of the global COP. We observed this extrapolation in our student interviews as students related their prior experiences in the local academic COP to the global professional COP. We observed them rely on their COP models to envision the activities of professional physicists and describe their own future physics-related careers. We identified points of alignment and misalignment between their COP model and the global COP. None of these students described an overall negative COP model, so there is additional space to explore with students of a greater diversity of outlooks.

Comparing models of different COPs helps a learner develop and negotiate their nexus of multimembership. Our research questions did not focus on nexus of multimembership, so we maintain this point tentatively. The students did compare experiences between their computationally integrated physics courses and their introductory programming courses, which are two different academic communities with different goals and practices. However, these discussions did not deeply probe their use of different COP models in these contexts.

Overall, we are satisfied with the insights afforded by this construct, and plan to explore further uses of the COP model. We are particularly interested in developing more detailed means of assessing or describing a student's COP model. For example, if the COP model is a map, can students draw one, or otherwise describe it in a way that can inform their instructors' teaching? Can we assess the degree of alignment between a COP model and the COP in reality, or at least highlight differences between a novice's COP model and an expert's COP model? Can we assess the students' perceived distance from the center of the COP? Developing a valid, reliable means of assessing a COP model would enable in-depth exploration of future research questions.

VII. CONCLUSIONS

We have reviewed the communities of practice framework and described a need to supplement this perspective with a consideration of how students perceive the community they are navigating. We described a construct, the COP model, that incorporates this student perspective by considering the mental model that the student develops to represent the community. The COP model includes the goals and practices of the community's sense of joint enterprise; includes the learner's sense of membership within the community; is developed in response to legitimate peripheral participation and feedback; enables the learner to extrapolate their experience of a local community to the broader community; and helps a learner negotiate their concurrent membership in multiple communities. We compared this construct with three other frameworks (figured worlds, possible future selves, and social cognitive career theory) to establish its unique affordances in the

COP framework. We illustrated the use of the COP model in explaining several key features of student interviews about their adoption of computational practices as they navigate the physics COP: partial alignment in the reasons for using computation; misalignment in their lack of confidence to carry out tasks that are not valued in the physics COP; and a misalignment between the expectations of many computationally minded physics instructors with students' experiences learning a new programming language. We have presented recommendations to further support computationally integrated student learning and outlined next steps for the exploration and use of the COP-model construct.

ACKNOWLEDGMENTS

We are grateful to the student interviewees for their time and insightful conversation, and to the instructors for their support of computation in physics education. This research has received no external funding. This work is supported by the University of North Florida.

APPENDIX: INTERVIEW MATERIALS

Items in square brackets were filled in based on the subjects' pre-interview survey and interview responses. An equals sign reminded the interviewer to record notes about a response to reference later.

1. Student pre-interview survey

Below are a few questions we'd like you to answer before your interview begins. We'll use your answers to customize your interview.

Pseudonym

During your interview, we'll refer to you by a pseudonym (false name) to help us keep your responses confidential. What pseudonym would you like us to use?

Background questions

In this section, we'll ask you questions about your background using computation in physics.

Please list all the physics classes in which you've used computation in assignments, class activities, projects, or other learning activities. By "computation," we mean the use of a computer programming environment (Jupyter, python, C++, JavaScript, etc.) to study a technical problem. Please include…

- The class name ("Modern Physics") or number ("PHY 3101").
- In what semesters (Fall 2020, Spring 2019, etc.) did you take each of these classes?
- Who were your instructors in each of these classes?
- On average, approximately how many hours did you spend each week on computational activities during each class?

Briefly tell us about any other learning experiences you've had involving computation (other classes, a training session or bootcamp, following on-line tutorials, etc.).

Tell us about your career goals. What type of work would you like to do after you graduate? What type of job would you like to have? What types of skills would you like to use or what types of activities would you like to be involved in?

(The CTAS questions [105] appeared here.)

2. Student interview protocol

I'm going to start with some questions about physics research.

1. When you picture a physicist conducting research, what kinds of activities do you imagine them doing? How do you think [activities] relate to each other? Which of [activities] do you see yourself doing in the future? Ask other probing questions as appropriate.

2. Why do you think physicists use computation in their research? How do you think computation relates to [activities]? Ask other probing questions as appropriate.

Next I'm going to ask some questions about your experience with computation in physics.

3. In [classes], what was one important physics concept you learned from your computational assignments? [Record their answer below.]

[concept] =

How did the computational assignments help you learn [concept]? Was [concept] something you already knew before the computational assignment, or was it something the computational assignment showed you for the first time? Ask other probing questions as appropriate.

4. IF Modern Physics in [classes]: Specifically, in Modern Physics, how did the computational assignments help you learn about the weird concepts in quantum mechanics? [Give examples of "weird concepts" as needed: particle-wave duality, tunneling, uncertainty principle] Can you describe an example? How did the computational assignments help differently than other aspects of the class, like reading the textbook or solving problems? Ask other probing questions as appropriate.

5. What sort of computational skills, if any, do you think every physics student should learn about? Ask probing questions as appropriate.

6. Describe how comfortable you felt working through the computational assignments in [classes]. Ask probing questions as appropriate.

Next, I'm going to ask some questions about your current thoughts about computation in physics.

7. Suppose you had to go back today and work a little more on the computational assignments from [classes]. Describe how comfortable you would feel now working through those computational assignments. Why do think you'd feel that way? Ask probing questions as appropriate.

8. Is there a class you're taking now where you might use computation or learn more about computation? Tell me

about that. How comfortable would you/do you feel using computation or learning more about computation in that class? Ask other probing questions as appropriate.

9. Are you working on any research projects right now where you might use computation? [If they say no or seem reluctant, you might want to broaden the definition of "research" to be "any study or investigation where you're trying to learn something new, either in class or out of class."] Tell me about that. How comfortable would you/do you feel using computation in that project? Ask other probing questions as appropriate.

10. When you see your future self as a [career goal], how do you see yourself using computation, if at all? IF affirmative answer: How comfortable do you think would you feel using computation like that? IF negative answer: Why is that? Ask other probing questions as appropriate. Specifically probe about…

How frequently they expect to use computation (regularly, infrequently, rarely).

To what degree they expect to use computation (central to their work, as needed to support their work).

In what ways they expect to use computation (modeling, data analysis, visualization).

11. What feedback or suggestions would you give to [instructors] about the computational assignments in [classes]? What aspects of the assignments worked well? What aspects of the assignments didn't work for you? What frustrated you about the assignments? How would you improve the experience? Ask other probing questions as appropriate.

I have one final question.

12. Is there anything else you'd like to go back to or add to our conversation? Ask probing questions as appropriate.

[1] Joint Task Force on Undergraduate Physics Programs, Phys21: Preparing Physics Students for 21st Century Careers 2016)), https://www.compadre.org/jtupp/report.cfm.

[2] E. Wenger, *Communities of Practice: Learning, Meaning, and Identity* (Cambridge University Press, Cambridge, England, 1999).

[3] E. Wenger, Communities of practice and social learning systems, Organization **7**, 225 (2000).

[4] E. Wenger, R. A. McDermott, and W. Snyder, *Cultivating Communities of Practice: A Guide to Managing Knowledge* (Harvard Business Press, Cambridge, MA, 2002).

[5] M. J. Ford and E. A. Forman, Chapter 1: Redefining disciplinary learning in classroom contexts, Rev. Res. Educ. **30**, 1 (2006).

[6] G. M. Quan, C. Turpen, and A. Elby, Interactions between disciplinary practice and joint work in undergraduate physics research experiences, Phys. Rev. Phys. Educ. Res. **14**, 020124 (2018).

[7] P. W. Irving and E. C. Sayre, Conditions for building a community of practice in an advanced physics laboratory, Phys. Rev. ST Phys. Educ. Res. **10**, 010109 (2014).

[8] E. W. Close, J. Conn, and H. G. Close, Becoming physics people: Development of integrated physics identity through the learning assistant experience, Phys. Rev. Phys. Educ. Res. **12**, 010109 (2016).

[9] P. Irving and M. Caballero, Understanding the PICUP community of practice, in *Proceedings of PER Conf. 2017, Cincinnati, OH* (PER Central, 2017), 10.1119/perc.2017.pr.042.

[10] P. W. Irving, D. McPadden, and M. D. Caballero, Communities of practice as a curriculum design theory in an introductory physics class for engineers, Phys. Rev. Phys. Educ. Res. **16**, 020143 (2020).

[11] S. L. Li and M. E. Loverude, Identity and belonging: Are you a physicist (chemist)?, AIP Conf. Proc. **1513**, 246 (2013).

[12] C. Fracchiolla, B. Prefontaine, and K. Hinko, Community of practice approach for understanding identity development within informal physics programs, Phys. Rev. Phys. Educ. Res. **16**, 020115 (2020).

[13] C. Rethman, J. Perry, J. P. Donaldson, D. Choi, and T. Erukhimova, Impact of informal physics programs on university student development: Creating a physicist, Phys. Rev. Phys. Educ. Res. **17**, 020110 (2021).

[14] J. Lave, Situating learning in communities of practice, in *Perspectives on socially shared cognition*, edited by L. B. Resnick, J. M. Levine, and S. D. Teasley (American Psychological Association, Washington, DC, 1991), pp. 63–82, https://psycnet.apa.org/buy/1991-98452-003.

[15] S. A. Barab and T. Duffy, From practice fields to communities of practice, Theor. Found. Learning Environ. **1**, 25 (2000).

[16] P. W. Irving and E. C. Sayre, Identity statuses in upper-division physics students, Cult. Studies Sci. Educ. **11**, 1155 (2016).

[17] M. Boylan, Deepening system leadership: Teachers leading from below, Educ. Manage. Admin. & Leadership **44**, 57 (2016).

[18] J. Boaler, Mathematics from another world: Traditional communities and the alienation of learners, J. Math. Behav. **18**, 379 (2000).

[19] E. Nardi and S. Steward, Is mathematics tired? A profile of quiet disaffection in the secondary mathematics classroom, Br. Educ. Res. J. **29**, 345 (2003).

[20] S. Wolfram, *A New Kind of Science* (Wolfram Media, Champaign, IL, 2002), Vol. 5.

[21] N. Chonacky and D. Winch, Integrating computation into the undergraduate curriculum: A vision and guidelines for future developments, Am. J. Phys. **76**, 327 (2008).

[22] R. F. Martin, Undergraduate computational physics education: Uneven history and promising future, J. Phys. Conf. Ser. **759**, 012005 (2016).

[23] J. Lave, E. Wenger *et al.*, *Situated Learning: Legitimate Peripheral Participation* (Cambridge University Press, Cambridge, England, 1991).

[24] M. Denscombe, Communities of practice: A research paradigm for the mixed methods approach, J. Mixed Methods Res. **2**, 270 (2008).

[25] P. W. Irving and E. C. Sayre, Becoming a physicist: The roles of research, mindsets, and milestones in upper-division student perceptions, Phys. Rev. ST Phys. Educ. Res. **11**, 020120 (2015).

[26] V. Otero, S. Pollock, and N. Finkelstein, A physics department's role in preparing physics teachers: The Colorado Learning Assistant Model, Am. J. Phys. **78**, 1218 (2010).

[27] P. C. Hamerski, P. W. Irving, and D. McPadden, Learning assistants as student partners in introductory physics, Phys. Rev. Phys. Educ. Res. **17**, 020107 (2021).

[28] N. W. Brickhouse, P. Lowery, and K. Schultz, What kind of a girl does science? The construction of school science identities, J. Res. Sci. Teach. **37**, 441 (2000).

[29] A. T. Danielsson, Exploring woman university physics students 'doing gender' and 'doing physics', Gender Educ. **24**, 25 (2012).

[30] A. J. Gonsalves, A. Danielsson, and H. Pettersson, Masculinities and experimental practices in physics: The view from three case studies, Phys. Rev. Phys. Educ. Res. **12**, 020120 (2016).

[31] I. M. Greca and M. A. Moreira, Mental, physical, and mathematical models in the teaching and learning of physics, Sci. Educ. **86**, 106 (2002).

[32] D. N. Rapp, Mental models: Theoretical issues for visualizations in science education, in *Visualization in Science Education* (Springer, New York, 2005), pp. 43–60.

[33] L. T. Louca, Z. C. Zacharia, M. Michael, and C. P. Constantinou, Objects, entities, behaviors, and interactions: A typology of student-constructed computer-based models of physical phenomena, J. Educ. Comput. Res. **44**, 173 (2011).

[34] I. Thacker and G. M. Sinatra, Visualizing the greenhouse effect: Restructuring mental models of climate change through a guided online simulation, Educ. Sci. **9**, 14 (2019).

[35] I. M. Greca and M. A. Moreira, Mental, physical, and mathematical models in the teaching and learning of physics, Sci. Educ. **86**, 106 (2002).

[36] D. L. Schwartz and J. Heiser, Spatial representations and imagery in learning, in *Handbook of the Learning Sciences*, edited by K. Sawyer (Cambridge University Press, Cambridge, 2006).

[37] K. Wade-Jaimes, K. Demir, and A. Qureshi, Modeling strategies enhanced by metacognitive tools in high school physics to support student conceptual trajectories and understanding of electricity, Sci. Educ. **102**, 711 (2018).

[38] J. Clement, Model based learning as a key research area for science education, Int. J. Sci. Educ. **22**, 1041 (2000).

[39] G. Knezek, R. Christensen, T. Tyler-Wood, and S. Periathiruvadi, Impact of environmental power monitoring activities on middle school student perceptions of stem, Sci. Educ. Intl. **24**, 98 (2013), https://eric.ed.gov/?id=EJ1015828.

[40] R. Christensen and G. Knezek, Contrasts in student perceptions of stem content and careers, in *Proceedings of Society for Information Technology & Teacher Education International Conference 2013*, edited by R. McBride and M. Searson (Association for the Advancement of Computing in Education, New Orleans, LA, United States, 2013), pp. 2048–2053.

[41] S. Y. Shin, L. C. Parker, O. Adedokun, A. Mennonno, A. Wackerly, and S. San Miguel, Changes in elementary student perceptions of science, scientists, and science careers after participating in a curricular module on health and veterinary science, School Sci. Math. **115**, 271 (2015).

[42] B. M. Means and A. Stephens, *Cultivating Interest and Competencies in Computing: Authentic Experiences and Design Factors. A Consensus Study Report* (National Academies Press, Washington, DC, 2021).

[43] A. M. Kelly, Social cognitive perspective of gender disparities in undergraduate physics, Phys. Rev. Phys. Educ. Res. **12**, 020116 (2016).

[44] A. B. Diekman, E. K. Clark, A. M. Johnston, E. R. Brown, and M. Steinberg, Malleability in communal goals and beliefs influences attraction to stem careers: Evidence for a goal congruity perspective, J. Personality Social Psychol. **101**, 902 (2011).

[45] T. A. Franz-Odendaal, K. Blotnicky, F. French, and P. Joy, Experiences and perceptions of stem subjects, careers, and engagement in stem activities among middle school students in the maritime provinces, Can. J. Sci. Math. Technol. Educ. **16**, 153 (2016).

[46] D. E. Agosto, S. Gasson, and M. Atwood, Changing mental models of the it professions: A theoretical framework, J. Info. Technol. Educ.: Research **7**, 205 (2008), https://www.learntechlib.org/p/111379/.

[47] A. B. Diekman, E. R. Brown, A. M. Johnston, and E. K. Clark, Seeking congruity between goals and roles: A new look at why women opt out of science, technology, engineering, and mathematics careers, Psychological Sci. **21**, 1051 (2010).

[48] S. Cheryan, J. O. Siy, M. Vichayapai, B. J. Drury, and S. Kim, Do female and male role models who embody STEM stereotypes hinder women's anticipated success in stem?, Social Psychol. Personality Sci. **2**, 656 (2011).

[49] S. Moshfeghyeganeh and Z. Hazari, Effect of culture on women physicists' career choice: A comparison of Muslim majority countries and the west, Phys. Rev. Phys. Educ. Res. **17**, 010114 (2021).

[50] L. Urrieta, Figured worlds and education: An introduction to the special issue, Urban Review **39**, 107 (2007).

[51] D. Holland, W. Lachicotte Jr, D. Skinner, and C. Cain, *Identity and Agency in Cultural Worlds* (Harvard University Press, Cambridge, MA, 2001).

[52] A. T. Danielsson, S. Engström, P. Norström, and K. Andersson, The making of contemporary physicists:

Figured worlds in the university quantum mechanics classroom, Res. Sci. Educ. **51**, 1141 (2021).
[53] S. Kapon, M. Schvartzer, and T. Peer, Forms of participation in an engineering maker-based inquiry in physics, J. Res. Sci. Teach. **58**, 249 (2021).
[54] J. H. Sisson, V. Whitington, A.-M. Shin, J. J. Thiel, and B. Comber, Communing to re-imagine figured worlds, Contemp. Issues in Early Childhood **23**, 32 (2022).
[55] A. L. Zuckerman and S. M. Lo, Transfer student experiences and identity navigation in stem: Overlapping figured worlds of success, CBE Life Sci. Educ. **20**, ar48 (2021).
[56] H. Markus and P. Nurius, Possible selves, Am. Psychol. **41**, 954 (1986).
[57] V. L. Vignoles, C. Manzi, C. Regalia, S. Jemmolo, and E. Scabini, Identity motives underlying desired and feared possible future selves, J. Personality **76**, 1165 (2008).
[58] J. Stevenson and S. Clegg, Possible selves: Students orientating themselves towards the future through extracurricular activity, Br. Educ. Res. J. **37**, 231 (2011).
[59] D. Bennett, L. Roberts, and C. Creagh, Exploring possible selves in a first-year physics foundation class: Engaging students by establishing relevance, Phys. Rev. Phys. Educ. Res. **12**, 010120 (2016).
[60] D. Verdín, A. Godwin, G. Sonnert, and P. M. Sadler, Understanding how first-generation college students' out-of-school experiences, physics and stem identities relate to engineering possible selves and certainty of career path, in *Proceedings of the 2018 IEEE Frontiers in Education Conference (FIE)* (IEEE, 2018) pp. 1–8.
[61] H. M. Lips, The gender gap in possible selves: Divergence of academic self-views among high school and university students, Sex Roles **50**, 357 (2004).
[62] R. W. Lent, S. D. Brown, and G. Hackett, Toward a unifying social cognitive theory of career and academic interest, choice, and performance, J. Vocational Behav. **45**, 79 (1994).
[63] R. W. Lent and S. D. Brown, Social cognitive model of career self-management: Toward a unifying view of adaptive career behavior across the life span, J. Counsel. Psychol. **60**, 557 (2013).
[64] C. Boothby and S. Milojević, An exploratory full-text analysis of science careers in a changing academic job market, Scientometrics **126**, 4055 (2021).
[65] Bureau of Labor Statistics, U.S. Department of Labor, Number of jobs, labor market experience, martial status, and health: Results from a national longitudinal survey, USDL-21-1567 (2021), https://www.bls.gov/news.release/nlsoy.nr0.htm.
[66] D. M. Bravata, S. A. Watts, A. L. Keefer, D. K. Madhusudhan, K. T. Taylor, D. M. Clark, R. S. Nelson, K. O. Cokley, and H. K. Hagg, Prevalence, predictors, and treatment of impostor syndrome: A systematic review, J. Gen. Internal Medicine **35**, 1252 (2020).
[67] J. K. Jr. and R. J. Sternberg, Perceived fraudulence in young adults: Is there an 'imposter syndrome'?, J. Personality Assess. **56**, 308 (1991).
[68] R. Tulshyan and J.-A. Burey, Stop telling women they have imposter syndrome, Harvard business review **31** (2021), https://bgsf.com/wp-content/uploads/2022/03/StopTellingWomenTheyHaveImposterSyndrome.pdf.
[69] I. Rodriguez, R. M. Goertzen, E. Brewe, and L. H. Kramer, Developing a physics expert identity in a biophysics research group, Phys. Rev. ST Phys. Educ. Res. **11**, 010116 (2015).
[70] P. R. Aschbacher, E. Li, and E. J. Roth, Is science me? High school students' identities, participation and aspirations in science, engineering, and medicine, J. Res. Sci. Teach. **47**, 564 (2010).
[71] R. M. Lock, Z. Hazari, and G. Potvin, Physics career intentions: The effect of physics identity, math identity, and gender, AIP Conf. Proc. **1513**, 262 (2013).
[72] Z. Hazari, D. Chari, G. Potvin, and E. Brewe, The context dependence of physics identity: Examining the role of performance/competence, recognition, interest, and sense of belonging for lower and upper female physics undergraduates, J. Res. Sci. Teach. **57**, 1583 (2020).
[73] D. P. Weller, K. Hinko, and V. Sawtelle, Investigating complementary computational and empirical activities for students learning diffusion, in *Proceedings of PER Conf. 2018, Washington, DC* (PER Central, 2018), 10.1119/perc.2018.pr.Weller.
[74] R. M. Serbanescu, P. J. Kushner, and S. Stanley, Putting computation on a par with experiments and theory in the undergraduate physics curriculum, Am. J. Phys. **79**, 919 (2011), 10.1119/1.3593296.3593296.
[75] R. Chabay and B. Sherwood, Computational physics in the introductory calculus-based course, Am. J. Phys. **76**, 307 (2008).
[76] N. T. Young, G. Allen, J. M. Aiken, R. Henderson, and M. D. Caballero, Identifying features predictive of faculty integrating computation into physics courses, Phys. Rev. Phys. Educ. Res. **15**, 010114 (2019).
[77] J. Weber and T. Wilhelm, Conceptual understanding of Newtonian dynamics in a comparative study of computational modeling and video motion analysis, in *Proceedings of PER Conf. 2021, virtual conference* (PER Central, 2021), 10.1119/perc.2021.pr.Weber.
[78] C. Singh, Interactive learning tutorials on quantum mechanics, Am. J. Phys. **76**, 400 (2008).
[79] S. McKagan, K. K. Perkins, M. Dubson, C. Malley, S. Reid, R. LeMaster, and C. Wieman, Developing and researching phet simulations for teaching quantum mechanics, Am. J. Phys. **76**, 406 (2008).
[80] B. Zwickl, K. Chen, J. Deslongchamps, A. Leak, and K. N. Martin, Characterizing analytical and computational mathematics use during, Ph.D. research, in *Proceedings of PER Conf. 2017, Cincinnati, OH* (PER Central, 2017), .
[81] C. Wang, J. Shen, and J. Chao, Integrating computational thinking in STEM education: A literature review, Int. J. Sci. Math. Educ. **19**, 1 (2021).
[82] C. J. Burke and T. J. Atherton, Developing a project-based computational physics course grounded in expert practice, Am. J. Phys. **85**, 301 (2017).
[83] C. Fracchiolla and M. Meehan, Computational practices in introductory science courses, in *Proceedings of PER Conf. 2021, virtual conference*, 10.1119/perc.2021.pr.Fracchiolla.

[84] K. Thornton, S. Nola, R. E. Garcia, M. Asta, and G. B. Olson, Computational materials science and engineering education: A survey of trends and needs, JOM **61**, 12 (2009).

[85] M. Caballero, Computation across the curriculum: What skills are needed?, in *Proceedings of PER Conf. 2015, College Park, MD* (PER Central, 2015), 10.1119/perc.2015.pr.015.

[86] R. A. Enrique, M. Asta, and K. Thornton, Computational materials science and engineering education: An updated survey of trends and needs, JOM **70**, 1644 (2018).

[87] A. L. Graves and A. D. Light, Hitting the ground running: Computational physics education to prepare students for computational physics research, Comput. Sci. Engin. **22**, 50 (2020).

[88] D. P. Weller, T. E. Bott, M. D. Caballero, and P. W. Irving, Developing a learning goal framework for computational thinking in computationally integrated physics classrooms, arXiv:2105.07981.

[89] D. Weintrop, E. Beheshti, M. Horn, K. Orton, K. Jona, L. Trouille, and U. Wilensky, Defining computational thinking for mathematics and science classrooms, J. Sci. Educ. Technol. **25**, 127 (2016).

[90] B. R. Lunk and R. Beichner, Attitudes of life science majors towards computational modeling in introductory physics, in *Proceedings of PER Conf. 2016, Sacramento, CA*, 10.1119/perc.2016.pr.047.

[91] A. Gavrin, G. Vemuri, and D. Maric, Preliminary efforts to evaluate an initiative introducing computation across the undergraduate physics curriculum, in *Proceedings of PER Conf. 2021, virtual conference*, 10.1119/perc.2021.pr.Gavrin.

[92] P. C. Hamerski, D. McPadden, M. D. Caballero, and P. W. Irving, Students' perspectives on computational challenges in physics class, arXiv:2202.07718.

[93] J. Krawitz and S. Schukajlow, Activation and monitoring of prior mathematical knowledge in modelling processes, in *Proceedings of the 42nd Conference of the International Group for the Psychology of Mathematics Education* (Psychology of Mathematics Education, Umeå, Sweden, 2018), p. 243.

[94] S. I. Hofer, R. Schumacher, H. Rubin, and E. Stern, Enhancing physics learning with cognitively activating instruction: A quasi-experimental classroom intervention study, J. Educ. Psychol. **110**, 1175 (2018).

[95] National Academy of Sciences, Engineering, and Medicine, *How People Learn II: Learners, Contexts, and Cultures* (National Academies Press, Washington, DC, 2018).

[96] M. D. Caballero, M. A. Kohlmyer, and M. F. Schatz, Implementing and assessing computational modeling in introductory mechanics, Phys. Rev. ST Phys. Educ. Res. **8**, 020106 (2012).

[97] D. P. Oleynik and P. Irving, Scientific practices in minimally working programs, in *Proceedings of PER Conf. 2019, Provo, UT*, 10.1119/perc.2019.pr.Oleynik.

[98] B. R. Lunk *et al.*, A Framework for Understanding Physics Students' Computational Modeling Practices., Ph.D. thesis, North Carolina State University, Raleigh, North Carolina, 2012.

[99] S. Weatherford and R. Chabay, Student predictions of functional but incomplete example programs in introductory calculus-based physics, AIP Conf. Proc. **1513**, 42 (2012).

[100] S. Weatherford, Student Use of Physics to Make Sense of Incomplete but Functional VPython Programs in a Lab Setting, Ph.D. thesis, North Carolina State University, Raleigh, North Carolina, 2011.

[101] M. D. Caballero and L. Merner, Prevalence and nature of computational instruction in undergraduate physics programs across the united states, Phys. Rev. Phys. Educ. Res. **14**, 020129 (2018).

[102] A. D. Robertson, R. E. Scherr, and S. B. McKagan, Paradigms in physics education research, arXiv:1307.4135.

[103] R. K. Yin, *Case Study Research: Design and Methods*, 3rd ed. (SAGE Publications, Newbury Park, CA, 2003).

[104] J. Rowley, Using case studies in research, Management Res. News **25**, 16 (2002).

[105] L. Apple, J. Baunach, G. Connelly, S. Gahlhoff, C. Megowan-Romanowicz, R. Elizabeth Vieyra, and L. Walker, Computational modeling in high school physics first: Postcards from the edge, Phys. Teach. **59**, 535 (2021).

[106] E. Drever, *Using Semi-Structured Interviews in Small-Scale Research: A Teacher's Guide*, Scottish Council For Research In Education (ERIC, Edinburgh, 1995).

[107] S. J. Taylor and R. Bogdan, *Introduction to Qualitative Research Methods: The Search for Meanings* (Wiley-Interscience, New York, 1984).

[108] S. Weatherford and R. Chabay, Student predictions of functional but incomplete example programs in introductory calculus-based physics, AIP Conf. Proc. **1513**, 42 (2013).