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Idaykis Rodriguez

STEM Transformation Institute, Florida International University, irodrig@fiu.edu

Michelle Goertzen

American Physical Society

Eric Brewe

STEM Transformation Institute and Department of Physics, Florida International University, ebrewe@fiu.edu

Laird H. Kramer

Department of Teaching and Learning and STEM Transformation Institute, Florida International University, kramerl@fiu.edu

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Developing a physics expert identity in a biophysics research group

Idaykis Rodriguez,¹ Renee Michelle Goertzen,² Eric Brewe,^{4,1} and Laird H. Kramer^{3,1}

¹*STEM Transformation Institute, Florida International University,
Miami, Florida 33199, USA*

²*American Physical Society, One Physics Ellipse, College Park, Maryland 20740, USA*

³*Department of Teaching and Learning, Florida International University, Miami, Florida 33199, USA*

⁴*Department of Physics, Florida International University, Miami, Florida 33199, USA*

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We investigate the development of expert identities through the use of the sociocultural perspective of learning as participating in a community of practice. An ethnographic case study of biophysics graduate students focuses on the experiences the students have in their research group meetings. The analysis illustrates how the communities of practice-based identity constructs of competencies characterize student expert membership. A microanalysis of speech, sound, tones, and gestures in video data characterize students' social competencies in the physics community of practice. Results provide evidence that students at different stages of their individual projects have opportunities to develop social competencies such as mutual engagement, negotiability of the repertoire, and accountability to the enterprises as they interact with group members. The biophysics research group purposefully designed a learning trajectory including conducting research and writing it for publication in the larger community of practice as a pathway to expertise. The students of the research group learn to become socially competent as specific experts of their project topic and methodology, ensuring acceptance, agency, and membership in their community of practice. This work expands research on physics expertise beyond the cognitive realm and has implications for how to design graduate learning experiences to promote expert identity development.

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I. INTRODUCTION

The model of a physics expert is traditionally defined by the cognitive abilities of experts, such as having large amounts of content knowledge and having superior memory retrieval mechanisms when solving problems [1]. Particular studies have focused on the abilities of physics experts to solve textbook problems faster and more effectively than student novices [2–4]. A salient and generalized feature of experts is that they acquired their expertise through 10 years of deliberate practice [5]. We deviate from this perspective and expand the model of physics expertise to be inclusive of the social and cultural aspects that develop expertise. There are social interactions and cultural experiences within the community of physics that are learned in the process of becoming an expert. We contend that being a physics expert carries certain social connotations about what kind of person one is and how one creates experiences and interacts within the community of physicists [6,7]. Taking the social-cultural perspective of learning as transforming one's participation in the social world [8–12], we examine how physics expertise is

developed when participating in the natural context of a community of physicists. We particularly analyze the enculturation process of biophysics graduate students into the larger biophysics community through their development of individual expert identities. We review theories of identity that support the social development of expertise of the individual as part of a community. This research study then expands the model of physics expertise beyond the cognitive realm to include the social factors that influence expertise development such as identity.

Graduate students in physics have a considerable attrition rate. About half of the students enrolled in graduate Ph.D. programs do not graduate with their physics Ph.D. within nine years [13]. Although some students may switch and finish with a terminal master's degree, such high attrition rates of graduate students is alarming, given the substantial amount of time and resources invested by the students, faculty, and departments [14,15]. Several factors influence doctoral completion and attrition, including disciplinary and departmental issues such as mismatched expectations between students and their departments [16–18], poor advising [16–18], structural isolation of students [15,16], and the misunderstanding of departmental research cultures [18]. Such research on graduate attrition, as well as the Physics Graduate Education Task Force [19,20], promotes the improvement of placement tests, communication skills, mentoring of students, professional development opportunities, and productive participation in

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the department; yet, attrition in graduate school remains high. Exploring the graduate education experience from the perspective of developing a physics identity provides an opportunity to see the influence of these factors on the students' experience. It can also suggest changes to graduate mentoring experiences that would nourish students' individual expert identities.

Understanding the development of a physics expert identity requires examining how physicists learn from a social-cultural perspective [21]. Social-cultural theories of learning see learning as a social process of engagement in the world and transforming one's participation in the world [8–12]. For example, the apprenticeship model of learning [22,23] suggests that a novice learns to become a master at a trade by participating in the activities of the trade. As apprentices develop their craft they become recognized for their craft. The apprentice changes from being an apprentice to becoming a master with a unique style and craft. The apprentice becomes a unique member of the community and contributes a specific expertise.

In physics, the socialization process of becoming an expert member of the community may start as early as the first introductory physics course in high school or college, but the experiences that help one become an expert member of the physics community, we argue, typically happen during graduate school [23,24]. Graduate school gives students the opportunity to select a field of study, a topic of interest, and a relevant question to investigate in the field. It is the place where the apprentices master the tools and skills to practice and evaluate relevant physics research. In Traweek's [25] seminal ethnographic study of high-energy physicists, she outlines three stages of being a legitimate and competent member of the high-energy physics community. The stages are undergraduate student, graduate student, and postdoctoral research assistant. Although Traweek claims the stage of postdoctoral research assistant is when one becomes a "full-fledge member" (p. 75), it is during graduate school that students develop the skills and knowledge to practice and evaluate physics research. Graduate school is often the time when students learn skills, such as how to use a specific research method, how to operate the equipment, and how to document and present their work [26].

In this ethnographic study, we observed graduate students for eight months in a biophysics research group in order to characterize their expert identity development. To frame our study, we first review the literature on development of identity in a community of practice. This framework guides our understanding of how expert identity develops in practice and is influenced by historical, social, and local structures in the group. We then use the constructs of membership competencies, which are not considered individual traits but involve interaction between students' opportunities to participate competently and the meanings they make of those opportunities [27]. These opportunities

are represented in three episodes of student interaction with mentors when the students are at different stages of their individual projects. The analysis of specific episodes allows us to observe how identity and competencies are enacted in a cross-sectional sample as a way of illustrating some developmental features of expert identity. As an analogy to the expert identity development of students in this research group, consider looking at different children of different ages and getting a sense about how general child development occurs. We summarize our research question to be how mentor and student interaction shapes the development of student's expert identity through social competency. We discuss how physics graduate students develop competencies towards expert participation in the research group and we argue for three socially constructed competencies that characterize the students' expert identities.

II. DEFINING IDENTITY

In science education, most studies on identity focus on specific aspects of the individual or specific "worlds" an individual can belong to, such as gender, race, ethnicity, nationality, or sexual orientation [28–32]. Science education literature has taken particular interest in the critical perspective of the female gender participating in science and mathematical fields [30,31,33,34]. Carlone and Johnson [30] modeled what they call "science identity" to have three dimensions: competence, performance, and recognition. Hazari *et al.* [34] added the dimension of interest to Carlone and Johnson's model of science identity. Both of these works on science and physics identity are not gender specific, but they research the interaction of science identity with aspects of an individual's cultural identities such as gender and race. Their model for science identity is contextualized in the defining characteristics of a specific scientific discursive community of which women are or aspire to be members and need the competence to participate within the community. The competence dimension in their science identity model describes that person's content knowledge.

Competence can also be expanded to include social engagement to produce knowledge, in other words, how to learn to behave and grow in the community of practice. The study by Feldman *et al.* [35] of chemistry graduate students gaining "proficiencies" (p. 234) during their graduate career refers to a social aspect of competence. They find that their chemistry graduate students develop two kinds of proficiencies, methodological and intellectual, in their growth towards expertise. Feldman *et al.* describe three levels of methodological proficiencies the chemistry students develop at different stages of their career. The first level, methodological proficiency, is the ability to gather and analyze data effectively. In the second level, the student masters a technique or machine and is able to manage their research and mentor others. The third-level methodological proficiency is when the student, in this case a doctoral

student, is able to innovate and develop new methods of research. The second kind of proficiency, intellectual proficiency, does not have distinct levels, but the student must be able to show the ability to create, disseminate, or defend new knowledge and research in the field. The ultimate goal for the student is to be aware and work towards becoming part of the larger field of research.

From the mentioned studies on competencies and proficiencies as describing part of one's identity, we learn what the technical and content competencies are, but the studies do not discuss the importance of socially developed competencies. The two studies, Carlone and Johnson [30] and Feldman *et al.* [35], discuss some of the possible skills and abilities gained by science graduate students during their development of expert identities. Carlone and Johnson and Feldman *et al.* define competencies and proficiencies through technical and content knowledge gained by the students. Neither study goes beyond performance and technical mastery abilities to distinguish interaction, engagement, and social competencies that develop as well. Intellectual proficiency discussed by Feldman *et al.* [35] does require the student to contribute work and publications to the field, which is essentially a social process of joining a community of researchers. However, they do not detail how intellectual proficiency develops or whether it is a defining characteristic of expertise.

In this paper we differ from the previous studies that define competencies only as content knowledge, and expand the definition to include socially constructed competencies developed through participation in a community. We take Wenger's [10] model of identity in a community of practice and focus on the specific aspect of someone's identity as defined by membership through social competence.

III. IDENTITY IN A COMMUNITY OF PRACTICE

A community of practice in its simplest form is a group of people that share a common practice [10]. For example, physics as a community of practice is wide and general in its pursuit to understand how the natural world works. Within physics there are subfields that also share their own specific goals and ways of approaching their questions, and they too are communities of practice. In this paper, we take a smaller unit of analysis as a community of practice: a physics research group. A physics research group is a community of practice as it has three defining characteristics of a community [10]. A research group and its members (1) mutually engage in the pursuit of a common goal, (2) negotiate meaning of their joint enterprise of research, and (3) share common tools, standards, norms, and traditions to get the job done. Most importantly, a research group is the context in which physics graduate students are expected to transition from students to researchers in the *practice* of physics research and therefore develop their specific expert identities.

Identity development in a community of practice is understood as learning through changes in participation in a social context [9,10]. We understand the concept of identity to be composed of multiple constructs and socially constructed worlds that individuals belong to, such as the social constructs of gender and the social frames of life, like political views. However, we use Wenger's [10] social theory of identity within a community of practice, which revolves around the individual, not as a lone object, but an individual as defined by the world to which they belong and with which they interact. Wenger's identity construct has many dimensions. To understand the development of a physics expert identity, we will focus on the dimension of identity referred to as community membership.

A. Identity as community membership

Expert identity in a community of practice is in part¹ defined by full membership within the community. Membership within the community is a matter of experiencing competence and being recognized as a competent member of the community [10]. Wenger's [10] identity dimension distinguishes three types of competencies: mutuality of engagement, accountability to the enterprise, and negotiability of the repertoire. In this content, competence is related to the social competence of how well members engage with other in the community, how well they understand why they do the things they do, and how well they share the resources and tools that allow them to be successful in the community.

The first type of competence, mutuality of engagement, is the ability to engage with other members of the group, to respond in kind to their actions, and to establish relationships in which mutuality is the basis for participation. As part of identity formation, the community practices take on a unique significance for each member. Each member finds a way to create a form of individuality in the practice. It is through the value of one's competence, what one can individually bring to the practice, and the ability to connect with the competence of others that mutuality of engagement produces meaningful contributions and knowledge. "To be competent is to be able to engage with the community and be trusted as a partner in these interactions" (Ref. [36], p. 229).

The second type of competence in community membership is negotiability of the repertoire. "The repertoire of a community of practice includes routines, words, tools, ways of doing things, stories, gestures, symbols, actions, or concepts that the community has produced or adopted in the course of its existence" (Ref. [10], p. 83). Negotiability of the repertoire pertains to our ability to interpret and make use

¹One's identity is not only defined by the social and external interactions with the community but also personal perspectives of oneself. We choose to only focus on the social aspect of identity for this paper.

of the repertoire. This requires enough participation (personal or vicarious) in a practice to recognize the elements of the practice. One can experience the repertoire through sustained and continuous engagement in the community. “To be competent is to have access to the repertoire and be able to use it appropriately” (Ref. [36], p. 229).

The third type of competence in community membership is accountability to the enterprise. Accountability to the enterprise is the ability to understand the enterprise of a community of practice deeply enough to take some responsibility for it and contribute to its pursuits. For example, a nutritionist will advocate for healthy snacks for her son and live a healthy lifestyle. It is the actions, choices, and interpretations that she learns to value because she is accountable to the larger enterprise of healthy nutrition. Being accountable to the enterprise gives us a certain perspective of the world and how we should behave in it. “Members are bound together by their collectively developed understanding of what their community is about” (Ref. [36], p. 229).

The above definitions of the three social competencies show the positive aspects of engagement in developing competency, but the social competencies can also rise through argumentative and conflicting interaction. That is, one can be mutually engaged in disagreement of the topic or discourse and still show how social competencies are affected by the outcome of the discussion. Depending on how any of these interactions support a person’s identity development, we can interpret progress towards expertise. We will focus on interactions that lead to expert identity development.

Interpreting identity as competent membership defines knowing and learning within a community as what would be recognized to be competent participation in the practice. Social competency within the community is characterized by mutual engagement, negotiability of the repertoire, and accountability to the enterprise, which define the development of one’s membership identity within the community. Acquiring these social competencies helps determine how one will behave and participate in the practice. For this study, the definitions of the social competencies are used to characterize and analyze moment-to-moment social interactions between mentors and students to determine how identity is enacted and, in turn, how students socially develop expertise. We explain how the social competencies are microanalyzed within the discourse of video episodes in the methodology section.

IV METHODOLOGY

To investigate the development of expert identity in a biophysics research group, we take a sociocultural perspective of learning. The sociocultural perspective of leaning interprets identity development as being socially constructed and supports the study design as an ethnographic case study [37] of a specific research group. Ethnography is a qualitative research design in which the researchers

describe and interpret the shared and learned patterns of values, beliefs, behaviors, and language of a culture-sharing group (Ref. [37], p. 68). Ethnography gives us the opportunity to observe the ongoing process of change that is highly contextual in identity development in the social practice. The case study in this paper is an instrumental case study (Ref. [37], p. 74) in which the researcher focuses on a specific question or phenomenon and selects a bounded system that illustrates the issue. Our case study focuses on a specific community of practice, a physics research group, and how it develops its members to become experts. To explore the patterns of this specific research group, one of us (Rodriguez) conducted participant observations, where we were granted access to the day-to-day activities of the research group. Ethnographies historically are an outcome of anthropological fieldwork [25,37], and like anthropologists, we documented observations in our field notes, which were corroborated with video recordings of group interactions. Field notes serve as the first analysis tool; they were where we recorded interesting interactions, quotes, and emerging feelings during the field observations. In this study, the field notes were a collection of time-stamped notes and reflections made while observing the group and their interactions.

One of us (Rodriguez) served as the main researcher for this study. She was a physics graduate student at the time of the study and was gradually accepted and able to participate in the biophysics research group’s activities. Although she did not participate in research projects, she was able to ask questions and make suggestions in the research group meetings. Her experience with physics gives this study a unique perspective of student development and interaction that physics “outsiders” would have taken more time to acquire. Since the researcher was a graduate student at the time of the study, her identity influenced how the participants interacted with her and conversely how she interacted with the data and analysis. This interaction is referred to as “reactivity” in qualitative research [38].

To address any validity threats related to researcher bias, we established three validity measures throughout the research project. The investigator practiced “reflexivity,” the process of reflecting in a journal how the researcher reacts to the data and analysis [39]. We also practiced triangulation, the use of multiple data sources to confirm emergent findings [37–39]. In this case, the data were from the participant observation, field notes, video recording of the research meetings, and personal interviews with participants. In this paper we analyze video data from the research meetings, corroborated with the researcher’s notes and reflections. To further ensure internal validity, we implemented peer review of data analysis, in which the main researchers met with multiple physics education researchers and reviewed the evidence for the claims made. Meeting and discussing the multiple interpretations of the data with different education researchers led to a

consensus on how to adequately corroborate a claim with evidence [39].

A. Data collection of group dynamics

Our research participants are part of a theoretical and computational biophysics research group at an American university. The research group is housed within the physics department and the members conduct research on models of protein structure formation. The participant group holds weekly research meetings every Friday afternoon. Research meetings last 4–5 hours on average. Their meetings are at a time and place where each member of the group has an opportunity to report on the week’s progress and ask for guidance and help from their peers and mentors if they come across issues or questions about their project. The ethnographic case study includes participant observations and video recordings of each research meeting for the months of January 2011 through June 2011. Data from the weekly research meetings allowed us to observe the ongoing evolution of the participants’ work in real time.

B. Participants

The participant research group is composed of two university physics professors and four students. Matthew (all names are pseudonyms), founder of the research group, is a tenured professor and holds an administrative position in the department. Prakul is an associate professor and has been part of the group for about six years. Between the two of them, they were mentoring three graduate students and one undergraduate student at the time of our data collection. Udit, a fourth-year graduate student, focuses his studies on structural fluctuations of proteins at different pressures and volumes. Hal, a third-year graduate student, focuses on structural fluctuations of fluorescent proteins using molecular dynamics calculations. Both Hal and Udit learned English as a second language, they have the same native language as professor Prakul, and they all speak English fluently. The third graduate student, Ike, a third-year graduate student, models the structural transitions of proteins in random coil to beta structure, which is the prevalent structure of several brain diseases such as Alzheimer’s disease. The undergraduate student, Louis, works on theoretical models calculating the energy of amino acids in alpha helix protein chains. He also learned English as a second language but speaks English fluently. During the data collection period, interested undergraduate students, other experts in the field, and collaborators on projects also visited the group research meetings.

C. Analysis of video episodes

We analyzed data of everyday social interactions within the physics research group meetings. The methodological benefits of ethnography allow the researcher to observe and examine group-level meanings that structure the group’s

activities and define “normal” behavior for the group [27]. We present three episodes of student identity enactment in typical group interactions between students and their mentors working on specific aspects of the students’ project. Based on more than seven months of observations, we determined that these interactions are typical in their weekly research meetings. To represent the best opportunities of students participating competently, we selected interactions between students and mentors when the participants are discussing suggestions and not just listening to presentations or explanations. This kind of speaker-hearer discourse allows for participants to receive feedback from each other and also allows for the analysis of social positioning between authoritative participants and less authoritative participants in conversations [40] and group-level meanings of social competency.

Science education research and cognitive expertise research often begin with *a priori* definitions of experts and expert traits, usually the researchers’ expected definitions. In cases when the participants’ definitions are considered, it is done so to see how closely they align with the *a priori* definitions. For example, research that examines teachers’ enactment of reformed inquiry-based instruction measures their enactment against a standard valued by the research community [27]. We consider an alternative perspective and ask, What counts as expert *in this setting*? Therefore, a situated definition of expert means that students become “certain kinds” of experts within the context of the research group. Our data corroborate three sources of data illustrated in Fig. 1 that explain the situated definition of physics expertise in the biophysics research group and also serves as the starting point for our episode selection.

The situated definition of physics expert is explained in the participants’ own definition of expert development practiced as a tradition in the research group [24]. We review the following findings: The biophysics group’s mentors, Matthew and Prakul, agree that the most important attribute of a physics expert is to “contribute to the

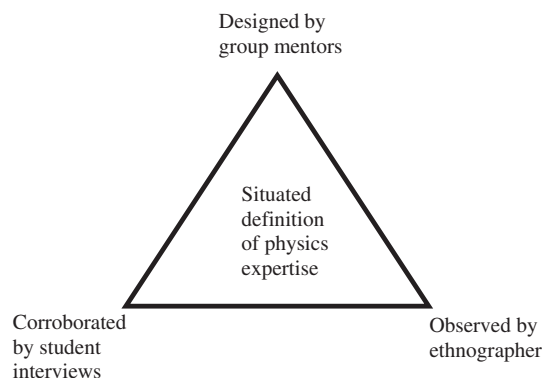


FIG. 1. Diagram representing different sources of data that illustrate the situated definition of physics expert as practiced in the research group.

scientific community” (Ref. [24], p. 320). Therefore, they prepare their students to “contribute to the field” by having them go through a general, but tacit, learning cycle of conducting research and writing manuscripts. The cycle involves students first contributing to the project by doing most of the research and literature review, as well as running simulations. The second part of the cycle requires the students to think about how the results and graphical representations help build the point of the manuscript. Finally, the students need to think about how the project contributes to the field as a whole and the future research implications. The episodes chosen for the analysis of expert identity development in this paper illustrate three points of this learning cycle: when a project is being designed or new research is being done (Ike), when experimental factors are being tested to build a stronger manuscript (Hal), and when the project is ready to be presented to the scientific community (Udit). A typical student in the group may complete more than one project in their graduate career with the group. Choices of data and data analysis were chosen based on the three stages expressed in the situated definition of expertise in the group.

Within each episode, we use microanalysis to identify the three kinds of social competencies. Microanalysis is a deep analysis of discourse in conversations and interaction where sounds, gestures, style, intonations, and talking turns are all evaluated to understand meaning and context [37]. Microanalysis of episodes with student and mentor interactions involves interpreting behaviors and actions during discourse in relation to a type of social competency. Mutuality of engagement is the ability to work together, and it can be analyzed within the episode as a whole where both student and mentor are working together in discussing some aspect of the project. Evidence of working together is found by cues in the discourse that show agreeable manner in the interaction, such as saying “yes,” “uh hum,” “ok,” not interrupting, or interrupting to finish the sentence. Discourse cues can also show a nonagreeable manner. Similar analysis of conversational boundaries of the whole episode can be used to understand the context of the conversation and the meaning and roles of the participants in the conversations. Both holistic and moment-to-moment perspectives of the episode will give insight to meaning within the discourses that will reveal social competencies of the interlocutors.

We show by example how the three social competencies of mutual engagement, negotiability of the repertoire, and accountability of the enterprise can be microanalyzed both holistically and moment to moment within an episode. Mutuality of engagement can also be analyzed from moment to moment when there is a conversation that ends in agreement in the positive or disagreement in the negative. Either positive or negative conversations can be evidence of mutuality of engagement. For example, when a

student and mentor are discussing the next course of action in the project, they both agree on testing a certain variable.

The second type of competency is negotiability of the repertoire. The repertoire includes “routines, words, tools, ways of doing things, stories, gestures, symbols, actions, or concepts that the community has produced or adopted in the course of its existence” (Ref. [10], p. 83). Being able to negotiate the repertoire, use the tools of the trade, do things a certain way, and “walk the walk and talk the talk” can be analyzed within the entire episode and moment to moment. In the case where the student is discussing simulation results, the entire episode is evidence for the student’s competence to use and manipulate simulation programs commonly used in the group. When the student is asked in discussion to follow a certain set of tests, the conversation become evidence of how the group follows procedures and whether the student has learned to do them.

The third type of membership competency is accountability to the enterprise. It is the ability to understand the practice and contribute to its pursuits. Accountability to the enterprise can be analyzed holistically where the entire episode is representative of actions taken by the participants to be accountable to the enterprise. For example, when preparing for a conference, the presentation is a form of research contribution that follows certain community conference rules or standards. Accountability to the enterprise can also be analyzed in moment-to-moment situations when conversations between participants revolve around issues central to the pursuits and norms of the community of practice. For example, when a question about the accuracy of the theoretical model of information provided is raised, the moment-to-moment discourse demonstrates accountability to the enterprise. In the following analyses of three episodes, both holistic and moment-to-moment analysis of each membership competency are described and following the analysis we also discuss the episodes’ theoretical connection to expert identity.

V. IDENTITY DEVELOPMENT THROUGH MEMBERSHIP

A. Designing an experiment

The first episode illustrates a typical discussion between mentors and a student determining the next steps in their analysis. The episode focuses on the work being done by Ike, a second-year graduate student with the group. Ike is working on the structural changes of a protein that is initially in alpha helix formation and transforms to beta fibrils. These protein structural changes are usually seen in proteins that are identified with Alzheimer’s disease. The group has developed a theoretical model that explains and predicts how the protein structurally changes as a function of time. The group received reviewer comments regarding their first manuscript submission, which recommended that they include how the size and shape of the proteins change

in the process. As part of the research, with the goal of including aggregate size in the current theoretical model, Ike has read experimental papers that describe the changes in aggregate protein size and shape for this process. Ike is in a meeting where the group is discussing how the data about aggregate size and structure from the experimental studies will be included in their theoretical computational model.

In this group meeting, Ike presents how he is able to convert the data about size of aggregates to an understanding of how it relates to rate of change in time. Ike has realized that the three experimental studies he has read are done in three different time scales and different initial conditions. In this episode Ike introduces the idea of changing the rate constants in their theoretical model in order to fit each of the three experimental data sets. Ike and his mentors then later conclude that the model stays the same. The three experimental studies are referred to as Lomaikin, Kirkatazi, and Fetzui.

Transcript conventions include the following: the boundaries of overlapping talk are shown with square brackets at the beginning ([]) and end (]) of the overlap, and emphasis in pronunciation is shown in bold. Gestures or actions are shown between angular brackets (<action>). Double dashes (--) represent an abrupt pause in conversation, while ellipses (...) represent long pauses of more than a second.

- (1) *Ike*: No. Well no-- Well, what I am saying is... I don't-- ...I...It's going to be really hard to compare... or to use the fits from any of the other papers for the Lomaikin data. Now what we could do is only fit to this here <points to equation on board that says "monomers per aggregate"> That's I mean--
- (2) *Prakul*: for Kirkatazi you mean?
- (3) *Ike*: No, for, for, for Lomaikin. Fit, fit to the number of aggre-- the number of monomers per aggregate and that's it.
- (4) *Matthew*: Because that is based upon the Lomaikin--
- (5) *Ike*: [Lomaikin data
- (6) *Matthew*: [data] the hydrodynamic radius. <glances at Prakul>
- (7) *Prakul*: And what about ours? We have the fit for the Lomaikin data as well?
- (8) *Ike*: No, no. The, the Lomaikin data does not have any secondary structure content.
- (9) *Prakul*: So what is the connection to our model then?
- (10) *Ike*: It's this. It's this here <Pointing at the monomer per aggregate equation on the board>. [number of monomers per aggregate.
- (11) *Matthew*: [Using]. Using the rate constants that we go from the Kirkatazi fitted--
- (12) *Ike*: No. No.
- (13) *Matthew*: Don't you use the rate constants from fitting the Kirkatazi data to then produce this?
- (14) *Ike*: Uh. Well I- ok. This, this particular one that I have drawn <points to a graph on the board> I use the rate constants from the Fetzui.

- (15) *Matthew*: [From the Fetzui.]
- (16) *Ike*: [What I'm saying is to get a whole different set of rate constants.
- (17) *Matthew*: To fit the Lomaikin.
- (18) *Ike*: To fit the Lomaikin. But we are only going to fit the number of monomers per aggregate. We are not going to fit any secondary structure data.
- (19) *Matthew*: From Lomaikin. There is none, right? There is none?
- (20) *Ike*: Yep, there is none.
- (21) *Matthew*: Ok.
- (22) *Prakul*: And?
- (23) *Ike*: Well I mean-- <Matthew chuckles>
- (24) *Prakul*: <looking at Matthew> Is that what you were--
- (25) *Matthew*: [No. No. I was going to say] <Prakul chuckles> What we are doing is, we are using our model to fit various experimental data from different groups,
- (26) *Ike*: [Yes]
- (27) *Matthew*: We are going to end up having to use different rate constants. The same model though, that one thing that will be the point of the paper: This model fits the data from several different experimental groups but we have to use different sets of rate constants depending on which type of data we are fitting. <Glances towards Ike> So -- I think that's what you are saying also.
- (28) *Ike*: Yes.

We now describe Ike's membership in this interaction as defined by the three types of competencies: mutuality of engagement, negotiability of the repertoire, and accountability to the enterprise in this episode.

Mutuality of engagement is the competence to work effectively in a group. To analyze this type of competence we look at the entire interaction and show evidence of how Ike is mutually engaged with his mentors and is recognized as a trusted participant on the project. Evidence for mutual engagement is given by the simple occurrence of having participants discuss projects and options for Ike's proposal at the weekly research meeting. In a moment-to-moment analysis we see Ike make a proposal to use different rate constants when fitting the different experimental results at the beginning of the conversation. Ike's mentors, Matthew and Prakul, try to understand what Ike is proposing by following Ike's train of thought and finishing Ike's sentences in voice turns 4, 6, and 11. In the efforts to understand Ike's proposal, the mentors also question Ike as a way of assessing the value and feasibility of Ike's proposal. Prakul offers challenging questions about the conceptual connection of Ike's proposal to change the rate constant of the established computational model. These intercepting questions are evidence of interlocutors trying to understand each other during discourse. In the interplay of finishing sentences and asking questions, both mentors

are formulating their own understanding of Ike's proposal and, by the end, Matthew summarizes his understanding of Ike's proposal in voice turn 27. Matthew reviews the points of discussion and concludes that the model will fit the different experimental results if they change the rate constants. Mathew's conclusion is in agreement with Ike's proposal and confirmed by both Ike, in voice turn 27, and Prakul with a nod (not shown in transcript). The student and the mentors have mutually resolved to accept Ike's proposal and, as a result, change the point of the manuscript.

For the second type of competence, negotiability of the repertoire, the participants must be able to use, manipulate, and exercise the tools of the practice, such as the computational software used to fit theoretical models with experimental results. Participants must also be able to communicate their ideas with language and logic common to the practice. Ike has effectively used the fitting programs used by the group to compare theoretical models to experimental results and has used this competence to recommend how to improve the group manuscript. Ike has also reviewed the relevant literature and has evaluated how his readings inform his model. Effectively learning to use such tools like computer software and reading relevant literature are skills developed through individual practice and effort. Negotiating more abstract tools of the repertoire, such as normative argumentation and language, is acquired from the social interactions with mentors and other group members. In this episode, Ike is given the opportunity to present his ideas for the manuscript and is challenged to clarify them during his presentation. Having the ability to use the resources such as argumentation and presentation skills during the meeting gives Ike the competence to clearly get his idea across to his group members.

The third type of competence, accountability to the enterprise, is the ability to weigh one's actions and decisions against the purpose of the overall larger biophysics and science enterprises. The inclusion of aggregate size analysis into their model is a result of a reviewer comment on the first manuscript. It is important to the research group to take up the request of the community of scientists they belong to and adhere to the standards of the field. In this interaction, the entire discussion of the different rate constants derives from the changes that need to be made to include aggregate size in the model. Moment-to-moment evidence of accountability to the enterprise is first shown by professor Prakul when he asks Ike to connect his proposal of different rate constants to the theoretical computational model in voice turn 9 and is implied again in voice turn 22. Prakul asked Ike how the proposal connected with the established theoretical model in order to gauge Ike's understanding of the theoretical model and the change in the model that Ike is suggesting. Prakul is doubtful of Ike's interpretations since they do not initially match his own. Earlier in the meeting, Prakul had stated that the

theoretical model was made to fit as many experiments as possible. Prakul ensures that Ike is learning to be accountable to standard research practice in the field by understanding the value of the theoretical model. There is no evidence that Ike did not already understand the difference between the original intent of the theoretical model and his proposed change. It was obvious from the interaction that his mentors question Ike in order to find out his understanding of the theoretical model and research process.

Analyzing for membership competencies in this episode helps us better understand what competencies a student might display at the beginning of a project. Given that the task is to investigate changes that need to be made to the computational model, the student and mentors together have the opportunity to develop the student's membership competencies by exposing the student to situations where he can present and argue a point. Although the discourse in this episode shows how the student is still being challenged to learn and is being evaluated on his efforts, the student is clearly valued as a member of the group that is learning how to manipulate the repertoire. The student's research procedures are thoroughly questioned by his mentors and he is still developing the social competencies to engage within the larger field of research. Designing an experiment is one of the first steps to developing expertise in physics.

B. Testing factors of the experiment

In the second episode, a third-year graduate student, Hal, and his mentors are discussing his project on green fluorescent proteins (GFPs). GFPs are of particular interest because they absorb and emit green light that can be used as biochemical markers for studying cellular processes. The proteins have a barrel-like surface with an oxygen sensitive chromophore that emits light at its center. Hal focuses his research on understanding the molecular dynamics of the protein when it is exposed to water in order to study how and when the chromophore becomes "quenched" by the oxygen and no longer emits light. Hal runs molecular dynamic calculations on a simulation program called CHARMM (chemistry at Harvard molecular mechanics) that is widely used by the biophysics field.

The episode starts in the middle of a four-hour-long research meeting when the group begins to discuss the progress of Hal's project. Hal is running simulations calculating the fluctuations in protein structure when the chromophore center interacts with water molecules. At the beginning of this episode, Hal is discussing what the program has been telling him about the location of the water molecules in the vicinity of the chromophore center. His mentors, Matthew and Prakul, inquire about the state of the interaction and how else to determine information about the location of the water molecules in relation to the chromophore center. In their discussion, they evaluate how the simulation program CHARMM is treating the

water molecules under given circumstances, such as if the water molecule is inside or outside the barrel.

- (1) *Matthew*: So there's a water molecule between beta seven and beta ten, can you tell that it is making a hydrogen bond to each one of them? Does CHARMM tell you if that is happening?
- (2) *Hal*: Hmm. In the sense of the distance, we can measure like, - choosing the amino acid from the beta strand and measuring the distance between the water molecule and the nearest hydrogen or oxygen.
- (3) *Matthew*: But CHARMM doesn't have any way to say, "is there a hydrogen bond between that water molecule and beta seven?"
- (4) *Hal*: Well either way it's measuring the distance.
- (5) *Matthew*: Just the distance
- (6) *Hal*: Yeah
- (7) *Prakul*: But maybe also the angle though.
- (8) *Hal*: For the CHARMM, they are not considering the angle...
- (9) *Prakul*: [what about?]
- (10) *Hal*: [it doesn't matter.]
- (11) *Prakul*: what about the other program that looks at the orientation because it's such a specific interaction.
- (12) *Matthew*: So you run it in CHARMM and then after you've got the output then you put it through a different program, which see about the angle.
- (13) *Hal*: <nodding> we can, we can use the VMD for that.
- (14) *Matthew*: Is your impression that the water molecule not only stays there, but stays in the same orientation while its there? Or does it move... does it rotate
- (15) *Hal*: Hmmmm. Maybe we can test that, if it is rotating or not.

In order to understand Hal's group membership development in this interaction, we will discuss evidence of the three types of competencies for community membership. In this episode, we see Hal mutually engaged with his mentors Prakul and Matthew in understanding the next step in the project. The relationship between the three of them constitutes their group and legitimizes Hal as a group participant. Their interaction shows a synergy between "complementary forms of competence and overlapping competence" (Ref. [10], p. 76) as they mutually engage. They are overlapping in that they all can visualize physically how the protein and the water interact and the structural changes that can possibly occur due to interactions. It is the complementary competence of the individuals—Hal's knowledge of the abilities and limits of the CHARMM program, Prakul's knowledge of the importance of orientation, and Matthew's ability to mediate the conversation—that brings the group forward into working effectively together to make meaningful decisions that create knowledge about the interactions between water and the protein. In a moment-to-moment analysis of the

discourse, we see that Matthew asks Hal how CHARMM functions to compute the information they need. Hal responds to the best of his knowledge of the limits of the program, but it is not enough to make a compelling argument. In voice turn 7, Prakul makes a suggestion of analyzing for the angle between the protein and the water molecules, and while CHARMM is not able to calculate this, another program can. Matthew immediately understands and mediates the discussion by summarizing the task (voice turn 12). Hal also understands the task to test for rotation and sees how to complete it on the VMD program. This example of complementary competencies between Hal and his mentors has created a flow of conversation where all participants clearly understand each other by the end of the conversation. It also shows Hal to be a competent member of the team and an important contributor on the project.

Hal also has the ability to interpret and make use of the group's repertoire. In this specific case, the episode shows evidence of how Hal negotiates the capacities and limits of the simulation programs that are commonly used in the biophysics field. Hal is able to determine how well the CHARMM program informs them about the hydrogen bond by measuring the distance. Since the distance measures were not enough, Hal was able to consider Prakul's suggestion of measuring the angle and knows what simulation program is able to complete the task, in voice turn 13. Hal has the competency to navigate multiple computational software programs that enhance his analysis and results. Hal has become a trusted member on the project and works well with his mentors to generate ideas. Hal's mentors see him as a student able to recognize the limitations of the analytical tool and who is aware of other tools that can be used instead.

For the third type of competence, we look for evidence of the participants being accountable to the enterprise. As a group, they have previously negotiated the purpose of the project to be to model where the water molecules are and how they are interacting with the chromophore center of the green fluorescent protein. Evidence for accountability to the enterprise is seen when professor Prakul asks Hal about measuring the angle between the water molecule and the chromophore in voice turn 7. Having multiple observable variables measured supports a robust analysis of water interacting with the chromophore. It is common practice for scientists to be responsible for conducting multiple tests and simulations and having all possible avenues explored before any conclusive statement is made of the observed phenomena. As such, it was important to have Prakul suggest an alternative variable to test. As a student, Hal has more practice with the daily technical routines of the computer simulations and sees the problem from a technical perspective. Having the opportunity to share the technical aspects of the project, as well as having advice on the fundamental physics behind the project from his

mentors, guides Hal towards envisioning the problem from a wider scientific perspective.

From the analysis of the interaction we can see a difference in the dialogue with Hal and the dialogue with the first student, Ike. Hal is in a more advanced stage of his project where he is comfortable with the analysis tools and is knowledgeable of the limits of his project. The dynamic between a student in Hal's position and his mentors is characterized by the quick exchange of knowledge and understanding. A student like Hal is asked for knowledge about the molecular dynamics simulations for the green fluorescent protein in his project, for example, while a student like Ike, at the beginning of a project, will be questioned on his knowledge about his project and whether he knows the value of the theoretical model of rate constants. Throughout the course of students' projects, participants have multiple ways to develop membership competencies. In the stage where the student is still testing multiple factors of the experiments, there is room to learn more about how the analysis reveals aspects about the physical phenomenon and why the physical phenomenon is important to study for the larger research community.

C. Communicating ideas

The third episode focuses on a student editing and reviewing his presentation for a national conference. Udit's presentation addresses his study of water penetrating into fluorescent proteins under different pressures. Like Hal, Udit has learned to use the CHARMM program to run molecular dynamic simulations of the fluorescent proteins, but he differs from Hal in that Udit looks at the proteins under different physical pressures.

Udit is a fourth-year graduate student in the biophysics research group, and although Udit has presented at national conferences before, this is the first time he will communicate his results on the topic of fluorescent proteins under different physical pressures. In this episode, Udit has just given a practice talk to his research group and he was over the time limit. He and his mentors are trying to figure out the best way to edit the presentation without missing any important points. We see how Udit's mentors, Prakul and Matthew, question and guide Udit to best edit his presentation. We also see Udit defending the choices he made for the presentation.

To better understand the dynamics of the interaction, we first unpack the physics that each participant is defending. The introductory slide to Udit's talk is about pressure and volume effects on fluorescent protein structure. At this point in the project, the group is only concerned with modeling protein "deformations" without specifying whether the protein is folding or unfolding. Denaturation is the process by which the protein loses its secondary or tertiary structure due to applied pressure or exposure to a strong acidic or basic solute. Denaturation is a phenomenon that the group is not considering for their project. Udit included

information about denaturation in his talk to educate his audience and as an introduction to pressure effects on protein structure. His mentors, in efforts to focus Udit's talk and have it under the time limit, feel that these details can be left out.

- (1) *Prakul*: This one also you can shorten. You spend a lot of time here. But, these were nice slides actually.
- (2) *Matthew*: [They work nicely]
- (3) *Prakul*: [... they are too familiar.]
- (4) *Matthew*: Yeah. You know, but you won't have - you don't have time to go into detail for these. You can read **each** of these points.
- (5) *Prakul*: And besides, this is more about folding than unfolding. We are not doing folding and unfolding.
- (6) *Matthew*: Well you see that, that's just it - - uh. These are nice slides but... it's not what we are looking at here.
- (7) *Udit*: But what I am connecting is to the pressure
- (8) *Ida*: [Isn't that-]
- (9) *Prakul*: [To the volume.]
- (10) *Udit*: The pressure on- the change of volume this, this, we are looking at this.
- (11) *Matthew*: But we are not looking at denage ratio [really.]
- (12) *Prakul*: [Yeah] we can't. <Prakul turns to Ida>. You had a [question.]
- (13) *Udit*: [But] what we are looking at the water penetration [while] protein folding.
- (14) *Matthew*: [Yes.]
- (15) *Ida*: Yeah, that's what I thought. I was like "oh the connects with-"
- (16) *Udit*: And the deformation also we are looking, we are saying we are trying to look at...
- (17) *Prakul*: "tends to deform" so, forget about unfold, worry about deform.
- (18) *Udit*: [I, I put it in.]
- (19) *Prakul*: "[Tends to deform] with increasing pressure." Ok remove unfold. Uh, and put temperature effect, the [pressure effect].
- (20) *Udit*: [But] it also unfolds so, at different pressures. We may not be able to go that high but-
- (21) *Prakul*: Exactly, but we are not doing unfolding, that's why... You don't want to distract people. You give an impression that, you know, you are doing simulations to show protein denaturation and you don't show any denaturation later on.
- (22) *Matthew*: I am going to... All this is true but I am going to remove this whole line. <deletes line at the computer>

This conversation is very fast paced, with no pauses, and overlapping talk, demonstrating that all participants are socially competent about the topic and skilled in presenting. In doing so, they are mutually engaged in trying to argue their point and negotiating what the consensus should be. Specifically, the mentors are first interpreting the slides

and evaluating what can be reduced or deleted in voice turns 4, 5, and 6. Udit tries to defend why he has included the points about pressure effects when he interjects and says, “But what I am connecting is to the pressure” and “But what we are looking at the water penetration while protein folding.” The next part of the conversation is the unfolding of the negotiation. In voice turn 17, Prakul suggests that Udit stay away from mentioning “unfolding” under pressure and that he just focus on “deformation.” Udit retorts that the proteins do unfold at higher pressures, which is a phenomenon their project could potentially analyze. Udit is bringing his own style and ideas of how the project can be presented. His mentor Prakul argues against not including the unfolding so that they will not distract the audience from the main point. The negotiation of ideas from participants is the fundamental point of mutual engagement, which enables them to generate useful knowledge in the interaction.

To analyze for the competence to negotiate the repertoire, we look at Udit’s use of tools shared by the group. Udit used PowerPoint software to write his talk, a common tool used by the research group, and in many cases by the community at large. Aside from his ability to use PowerPoint for presentations, Udit’s competence to negotiate to repertoire can also be seen by his understanding and use of research-specific terminology such as “folding,” “unfolding,” “denaturation,” and “denage ratio.” Language and jargon interchanged in conversation between participants to further explain their meaning requires all participants, in this case Udit, to have the ability to recognize critical elements of the practice. It is at this important stage of the project, presenting results at a national conference, when language, style, form, and standards of the practice can be displayed by the student or developed in the process.

When we analyze for the third type of competence, accountability to the enterprise, we see participants holding themselves accountable to the practice through their use of arguments and argument language. From the perspective of accountability, Udit’s defense of including unfolding and deformation due to water pressure is his way of being accountable to his audience. The purpose of including background information on pressure effects is to educate his audience. We also see his mentors holding themselves accountable by arguing for the valued standards of the community to not go over the allotted time of the presentation and to keep the information focused on the specific topic. The entire discussion in this episode is representative of all participants comporting themselves as accountable to the enterprise.

In this episode of the student learning to communicate his ideas, we see more argumentative dialogue and interruptions between interlocutors, where participants are trying to justify their point in the discussion. The student is also learning how to best prepare to present at

conferences. In preparing to communicate his results to the larger biophysics community, the student is showing his ability to perform all the expected duties and requirements of the project. At this stage of a project, the student is very familiar with the results and the research process; it is at this stage that he has an opportunity to best present his work. Communicating his work to the larger research community would require an understanding of the social competencies, or how to socially interact with the community and become a member. This third episode represents the later stages of the research process that graduate students in this research group complete.

All three episodes represent a learning cycle for a typical graduate student participating in the biophysics research group. Each stage in the cycle leads to new moment-to-moment opportunities to learn the social competencies of community membership.

VI. TRAJECTORY TOWARDS EXPERT MEMBER IDENTITY

Developing an expert identity is temporal in nature. It changes with every new generation of physics students interacting with their mentors. To teach new members of the group how to become experts in the field, mentors looked at their own past, the student’s present, and the future of the research group to inform the student’s trajectory towards specific expertise. Therefore, following from their own experience in graduate school in physics, the mentors in this biophysics research group designed a way for the students to become specific experts by contributing research to the scientific community. Along the way, with the experience of their own research projects, the students also develop their specific expert membership competencies. The students can see the importance of learning from their mentors’ past experiences and can create a trajectory with their own individual choices based on the future of research in the group and in the research field. In this biophysics research group, each student has their individual project and with that comes specific expertise in software manipulation and specific literature readings. In addition, the students are guided through their projects in stages represented in the above episodes: designing an experiment, testing any and all factors that influence the experiment, and preparing to communicate their contributions to the scientific community [24].

Table I demonstrates the discourse in each of the three representative episodes of a typical learning trajectory. The characterization of the discourse in each episode portrays how the microanalyses of competencies can be generalized to describe the development of identity of a typical graduate student in the research group. The first episode is representative of a student designing his project. Ike, the student in this example, proposed a change to a mathematical model of a process of change for a protein from alpha helix to beta fibril. He read relevant literature and argued for a

TABLE I. Competencies developed during learning trajectory.

Learning trajectory	Context	Characterizing discourse
Designing an experiment (Ike)	Makes a proposal to change the rate constants to include aggregate size.	Mentors question and evaluate proposal. Same point has to be explained twice.
Testing experimental factors (Hal)	Uses molecular dynamics simulations to understand water paths in GFP.	Student is trusted for his knowledge on the simulation program. Yet, there is room for improvement in suggestion from mentor.
Communicating and contributing to the field (Udit)	Negotiates the important points to include in his presentation for a national conference.	Dialogue is interruptive, where everyone participating has a voice and wants to be heard.

change to the model so that it included aggregate size. As Ike presented, his mentors questioned and evaluated his proposal. At first the mentors thought they knew what the student was proposing, as demonstrated by the fact that they finished his sentences, but when Ike explained it again, the mentors were confused. They asked him more clarifying questions to evaluate the steps taken to come to the proposal to change the rate constants in the mathematical model. One of the mentors also evaluated the purpose of the model. The undertones in the dialogue and interruptions demonstrated that the mentors were approaching Ike's proposal with certain skepticism. All good scientists have a certain degree of skepticism for methods and conclusions. Evaluating Ike's proposal is a social way of teaching a beginning student how scientists behave.

Unlike the student in the first episode being evaluated, the student in the second example is asked for advice. Hal is the student working on using molecular dynamics simulations of water pathways in green fluorescent proteins. Hal is at the stage in his project where he is well versed in the simulation program he uses and understands the outcomes of his program in the context of his project. A student at the stage of his project, who is able to talk comfortably about the methods and tools used to achieve a certain result, has already demonstrated specific expertise in that task. The dialogue with Hal shows how the mentors asked Hal for his knowledge, not because they are questioning his knowledge, but because they wanted to learn themselves. Yet there is also room for improvement when the mentors make suggestions on the next steps to take for his project.

The episode representative of the last stage in the learning trajectory is Udit preparing to communicate and contribute his research to the larger field of biophysics. The student is preparing for a presentation he is to give at a national conference. He goes over the time limit and has to rearrange his slides to include the information he needs and also to be within the time limit. We characterize the dialogue with his mentors to be interruptive. Every interlocutor in this episode has a voice and wants to be heard. The student included the background information to

educate his audience, while the mentors explained that they could not include everything because the presentation needs to be focused and brief. The student is at a stage where he is ready to present results and conclusions of his project to the larger community of practice. At this moment he felt the need to defend his work. The mentors make sure the student is ready by ensuring he does a practice talk and helping him hone the presentation to community standards, because the student is also a reflection of their ability to train the new generation of biophysicists in the community.

The last stage in the learning trajectory is a critical point when defining one's membership identity. When a student, like Udit, is given a voice to share his research with the larger research community, they then have agency to publicly share their created knowledge. Agency, or an individual's ability to shape the world around them [41], is widely studied in science identity research (see reviews in Refs. [41,42]). Having the agency to shape the knowledge of the practice is powerful in defining oneself as being part of a certain community of practice. Therefore, to be viewed as an agent of the knowledge clearly defines expertise within the practice. Expert identity, socially developed in a community of practice through the paradigmatic trajectory shared in this biophysics research group, guides the students to develop a specific expertise in their own project topic.

The episodes representative of the learning trajectory show moment-to-moment opportunities for students to be mutually engaged, negotiate the repertoire, and be accountable to the enterprise to socially develop their membership identity.

VII. IMPLICATIONS AND CONCLUSION

This study illustrates how expertise in a community of practice is a matter of identity formation through competent membership. With the support of the theoretical perspective of socially constructed expert identity development through the apprenticeship model of learning [10,22,23], we expand the literature on physics expertise beyond the cognitive

realm. This analysis shows the utility of considering expertise beyond the cognitive competency and efficient problem solving in physics. Further, we consider expertise as a process with differing states of being and experiencing, much more as a state of identity. Identifying social markers of expertise development and qualitative sources of data and analysis add to the current cognitive model of physics experts. An expansive expertise model can inform us of how physics experts behave in different contexts such as classrooms, solving problems, or in a research setting as shown by this study. We must do additional research or make inferences to learn about the other settings. An expansive physics expertise model can also teach us the cognitive and context-dependent experiences that characterize expertise in physics. This study identifies the social interactions that are effective for the individuals in this biophysics research group and provides an explanation of how students develop their specific physics expert identities.

A. Learning from group members

In the specific community of practice of the participant biophysics research group, the journey to specific physics expertise is guided by a learning trajectory designed from successful physicists such as “old timers,” past members, or mentors. The biophysics research meetings serve as a platform for advising students on their specific project and any issues they face. Students observe their peers’ problems and all the issues dealt with at different stages of their project. Students also have the opportunity to listen to stories of past experiences from experienced members in the practice. These experiences from the past, present, and future create a set of possibilities for a new student to negotiate in the formation of their own identity. As a form of individuality, each student in the biophysics group has their own topic of expertise: Ike specialized in protein structural changes from alpha helix to fibrils, Hal specialized in molecular dynamics simulations of green fluorescent proteins with the use of CHARMM, and Udit specialized in pressure and volume effects on protein structural changes. As the students are given the opportunity to present their own projects to their mentors, they are given feedback on their participation in the research group. In the social interaction of discussing projects, students and mentors have moment-to-moment opportunities to teach and learn the socially accepted competencies of behaving and being biophysicists.

B. Effective mentoring practices

These results point to the need for mentors to perceive their interactions with their graduate students as opportunities for social development of expert identities and group membership. Having an explicit plan or guide of how to involve students in group projects and having them lead their own projects to fruition and publication or

presentation at a conference builds student membership identity as a specific expert in their project. Working together on a project and discussing student’s ideas about the project assures the student that they are part of the group and develops mutual engagement within the group. Asking students their opinion on their project methodology or simulation program recognizes the student as specific experts in their projects and can show them how they have internalized the norms of the practice. Finally, and most critically, mentors should expose their graduate students to the standards and norms of the larger physics community by preparing them to present at national conferences and (or) submit their projects for publication, which undergoes peer review. The social understanding of how the larger field evolves and how one can develop agency to change it is the essence of becoming an expert in that field.

This study focused on student development of expertise in the specific context of their physics projects. We do not expect that every physics research group will follow the same practices as the participant biophysics group. Every group, as a community of practice, has their own specific norms and their own way of doing things. Our findings on practices situated in the context of scientific research groups guide students, mentors, and instructors on practices that could more effectively and explicitly develop social competencies. The study as a whole shows how interactions between mentors and students develop their social competency to participate in the scientific community at large. Through these interactions, students are socialized to become expert participants of the community. The participant biophysics group serves as a model of effective graduate student practices for those in search of improving their group dynamics and productivity. As the students in this research group develop their specific expert identities, we also see what kinds of experiences help them achieve their graduate career goals.

Aside from a healthy student-advisor relationship needed for success in graduate school [14,15], it is important to have professional development experiences [13]. We illustrate how the membership competencies of mutual engagement, accountability to the enterprise, and negotiability of the repertoire are developed socially and are related to professional development skills that students need beyond content knowledge. For example, for the students in this biophysics research group, the ability to manage one’s own project, analytically design and test experiments, and effectively communicate results in writing and presentations are professional skills useful in addition to content knowledge. These skills are necessarily useful in different contexts within and beyond the academic research world. Therefore, we aver that a socially constructed model of physics expertise through identity formation complements the established cognitive abilities of physics experts.

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