ABSTRACT: This study sought to understand how graduate and undergraduate students learn to do science by participating in research groups. A phenomenological approach was used to illuminate the experiences of the students. The results provide evidence that the students were in the role of apprentices, although this was not made explicit. As apprentices they learned by doing as legitimate peripheral participants in the groups. Mentoring was distributed among the group, with more advanced students providing much of it. The groups were both communities of practice and epistemic communities in which students gained methodological and intellectual proficiency. Finally, student learning in research groups can be conceptualized as learning trajectories that enter the group, traverse characteristics of communities of practice and epistemic communities, and leave with the students as novice researchers, proficient technicians, or knowledge producers. The implications for K-12 science education are that it is unrealistic to expect teachers to achieve the proficiency in traditional short-term research experiences that would prepare them to teach their students how to engage in authentic scientific research, and that these experiences should be structured so that the teachers are placed in tightly organized research groups with mentors who explicitly teach them how to do science. © 2013 Wiley Periodicals, Inc. Sci Ed 97:218–243, 2013
INTRODUCTION

Our purpose in this study is to better understand how students learn to do scientific research while participating in research groups. Although there has been extensive research on how scientists do science from both cultural and cognitive perspectives (e.g., Collins, 1985; Latour, 1988; Nersessian, 2005; Pickering, 1995), there are few studies that provide a comprehensive model for understanding the learning trajectories (Wenger, 1998) of students from their first entry into a science research group to the attainment of their degrees. It is our goal to provide readers with the beginnings of such a model.

Our study is also important for science education for several reasons. First, new scientists learn to practice science by engaging in scientific research projects. Although they learn a great deal of science content in formal coursework as undergraduate and graduate students, they are seldom expected to take courses in research methods, other than possibly statistics or courses in instrumentation. This is in stark contrast with our students in science education who are often required to take courses in research methods and design. Therefore, we believe that it is important to know what it is about students’ participation in research groups that leads to their ability to engage successfully in scientific research.

Second, we believe that the results from our study can help improve the education of new scientists. We also believe as science teacher educators that a better understanding of how students learn in research groups can serve in the development of better methods for teaching pre- and in-service science teachers how to do scientific research. This is especially important in response to the decades-long call for teachers to teach science as inquiry and to teach K-12 students how to do scientific inquiry (e.g., National Research Council, 1996; OECD, 2003). If we want teachers to be able to teach others how to do research, they need to know how to do it themselves.

In this study, we look at the participation of graduate and undergraduate students in research groups that made up an interdisciplinary project on the natural remediation of acid mine drainage. We interviewed the students and their faculty advisors, all of whom were principal investigators (PIs) of the project and observed the students and the professors as they participated in journal club meetings, did fieldwork, and made presentations to their peers. Our results provide evidence that the students took on the role of apprentices who learned by doing as legitimate peripheral participants in the groups. The students’ participation in the groups, we argue, follow learning trajectories whereby they enter the group, traverse characteristics of communities of practice and epistemic communities in which they gained methodological and intellectual proficiency, and then leave as novice researchers, proficient technicians, or knowledge producers.

LITERATURE REVIEW

Our research is focused on how students learn to do scientific research through their participation in research groups. This suggests that our review of the literature ought to include work in science studies of how science is done in practice (e.g., Collins, 1985; Latour & Woolgar, 1986; Pickering, 1995). While there is much in these studies about how science is done, there is little in these works about how students learn the methods of science through participation in research groups. As Delamont and Atkinson (2001) noted, “the academic and scientific enculturation of scientists through doctoral research training has received little explicit attention in the research literatures of the sociology, and anthropology of science and technology, the sociology of the professions and the sociology of education” (pp. 88–89). The lack of research on the relationship between the work that new scientists do in research groups and their training has also been noted by
Warwick and Kaiser (2005) in their book on pedagogy and science practice. The chapter by Traweek (2005) stands out as an exception. It looks specifically at the training of new physicists in laboratories, rather than, for example, the role of textbooks (García-Belmar, Ramón Bertineu-Sánchez, & Bensaude-Vincent, 2005) or how changes in pedagogy affect research (Goody, 2005). Traweek’s focus, however, is at the macrolevel, looking at how historical and societal changes in Japan affected the culture of high-energy physics, and in turn, the training of physicists.

More recently, Nersessian (2008) noted “learning in laboratories— instructional and research—is an essential part of becoming a scientist today, yet it scarcely has been studied” (p. 59). That said, Nersessian’s work does provide us with a window into research laboratories and how they provide opportunities for the types of learning experiences that support the growth of researchers from novice to experts. We return to her work later in our review.

Although there is little in the field of science studies that focuses on the development of new researchers in research groups, there has been a fair amount of research on what Sadler, Burgin, McKinney, and Ponjuan (2009) refer to as research apprenticeships. This includes the extensive work done on precollege students (Barab & Hay, 2001; Charney et al., 2007; Etkina, Matilsky, & Lawrence, 2003; Richmond & Kurth, 1999), undergraduates (Hunter, Laursen, & Seymour, 2007; Kardash, 2000; Lopatto, 2004; Rauckhorst, Czaja, & Baxter Magolda, 2001), and pre- and in-service teachers (Pop, Dixon, & Grove, 2010; Schwartz, Lederman, & Crawford, 2004; Varelas, House, & Wenzel, 2005) engaged in short-term research experiences. Because our study focuses on undergraduate and graduate students, we look more closely at that literature.

Undergraduate Research Experiences

We reviewed four studies that examined what students learn in undergraduate research experiences (Kardash, 2000; Laursen, Hunter, Seymour, Thiry, & Melton, 2010; Lopatto, 2004; Rauckhorst et al., 2001). These are among the most cited studies of undergraduate research experiences (UREs). We begin with Lopatto (2004), who developed the Survey of Undergraduate Research Experiences (SURE), which is now in its third form.¹ His goals were to determine (a) whether the students’ educational experiences were enhanced, (b) if the UREs attract and support talented students interested in careers that involve scientific research, and (c) if the UREs help to retain minority students in the pathway to scientific careers. Given our interests, we are most concerned with the findings related to his first goal. His survey included students rating 20 evaluative questions derived from previous research on possible educational gains from UREs. Lopatto found that the highest rated item was “understanding of the research process in your field,” followed by “readiness for more demanding research,” “understanding how scientists work on real problems,” and “learning laboratory techniques.” Each had a mean of 4.0 or above on a scale of 1–5 with 5 being “very large gain.” The lowest rated items included “learning ethical conduct,” “skill in science writing,” “skill in oral presentation,” “clarification of a career path,” and “self-confidence.” Some of the items with means from 3.5–4.0 include the interpretation of results, analysis of data, and understanding the primary literature. As can be seen, the possible benefits provided to students in SURE are wide ranging from broad and ill defined (e.g., understanding how scientists work) to the particular skills needed to do scientific research (e.g., analyze data). More importantly, when students select “very large gain” rather than “small gain,” it tells us little about what the students actually learned, what they

¹The SURE I survey is not described in his 2004 paper. However, we were able to access the SURE III at http://www.grinnell.edu/academic/csla/assessment/sure, and it appears that the 20 items are the same.
came to understand about the research process, or how skilled they are in doing research at the end of the research experience.

Kardash (2000) also used a survey to measure students’ perceptions of their UREs. However, she asked the students to rate their abilities to perform research skills at the beginning and end of the URE and also asked their mentors to rate them. As a result, we can see changes in students’ perceptions of their abilities over the URE, which are triangulated with their mentors’ perceptions. Kardash found that faculty and undergraduate students agreed that the students had increased their ability to observe and collect data, understand the importance of controls, interpret data, orally communicate their results, and to think independently. Faculty and students “rated as low the skills of identifying a specific question for investigation, formulating a hypothesis, and designing a test of the hypothesis” (pp. 196–197). The lowest ratings were for the skills needed to make use of research literature, relating one’s research results to the big picture, and writing a research paper.

Laursen et al. (2010) conducted interviews with 76 students engaged in undergraduate research at four liberal arts colleges. The students, their mentors, and administrators were interviewed, as well as students and faculty not involved in UREs. Laursen et al. analyzed the transcribed interviews for evidence of reported gains from the UREs. They grouped the gains into six main categories, which are listed here from highest to lowest: “Personal/professional gains; Gains in thinking and working like a scientist; Gains in becoming a scientist; Gains of skills; Enhanced preparation for career and graduate school; and Clarification, conformation, and refinement of career and educational goals and interests” (p. 45). As with Lopatto’s and Kardash’s studies, Laursen et al. found a wide variety of benefits for students from such experiences. However, Laursen et al. note that by the end of the summer, there were “only small numbers [of students] who saw themselves as able to think creatively about research design or to comprehend how scientific knowledge is created” (p. 202). They see this finding as being in line with Kardash’s and those of Rauckhorst et al. (2001), to which we turn next. In an earlier paper, Hunter et al. (2007) argue that this can be understood using Baxter Magolda’s (1992) categories of ways of knowing to understand how undergraduates develop intellectually while engaged in research apprenticeships.

The Rauckhorst et al. (2001) study specifically used Baxter Magolda’s categories as a way of understanding student learning in UREs. They found that few of the undergraduates they studied saw knowledge as certain or absolute (Category 1) at the beginning of the experience, with most having a less absolute view and the ability to begin to use processes to search for truth (Category 2). Compared to a control group, there was a much larger movement from Category 2 to Category 3, in which students begin to think for themselves and question the absoluteness of expert knowledge. However, by the end none of the students reached Category 4, in which “students believe that theories are constructed in a context based on judgment of evidence; their role is to exchange and compare perspectives, think through problems, and integrate and test theories” (p. 5).

The findings from the studies reviewed above suggest that while research experiences for undergraduates are highly successful in helping them to develop technical research skills, they are less likely to promote student’s ability to engage in the higher order intellectual skills such as those used by expert scientists to originate and complete a research study.

Graduate Research Education

As we noted above, there has been little research done on the ways that students learn to become scientists through their participation in research groups. We acknowledge the
significant body of work on research groups from social and cultural perspectives (e.g., Collins, 1985; Latour & Woolgar, 1986; Osbeck, Nersessian, Malone, & Newstetter, 2011; Pickering, 1995). However, these studies do not provide us with a comprehensive model for the learning that occurs from the time that inexperienced students join research groups until they complete their degrees. In this section, we review three studies that do this to some extent (Bucher & Stelling, 1977; Osbeck et al., 2011; Stucky, 2005). We then provide an overview of our previous work in this area.

We begin with Bucher and Stilling’s (1977) study of the professional socialization of “trainees” (their term) in four programs: two that prepared psychiatrists, one in internal medicine, and the fourth in biochemistry. The biochemistry trainees were graduate students in a biochemistry department located in a medical college. They participated in the faculty members research programs, receiving funding, and making use of their laboratories. The students progressed through the graduate program by clearing a series of hurdles: successful completion of required courses, two language examinations, a comprehensive examination, the qualifying examination, and finally the dissertation. The time devoted to laboratory work, and to their research, increased over time. Although they provide few data to support the claim, Bucher and Stilling state that the biochemistry students learned research methods “through a process of trial, error, and retrial, with occasional help from other people” (p. 93). The students continued to learn this way until their advisors were satisfied that they had the ability to write and publish scientific papers.

Stucky (2005), under the guidance of Bond-Robinson, studied an organic chemistry research group at a midwestern research university in the United States. Much of what Bucher and Stilling found in 1977 was still relevant in 2005. However, Stucky focused her inquiry on the ways in which knowledge is shared and learning takes place among the participants in the group. She used the theoretical perspective of situated cognition within communities of practice (Lave & Wenger, 1991; Wenger, 1998) to frame her study (Bond-Robinson & Stucky, 2005) and found that the students learned skills such as specific research methods, how to use complex equipment, and how to document and disseminate their work. They also learned the language and culture of the research group. Much of this learning occurred when students encountered “problems associated with equipment, materials, and instruments, lack of relevant background knowledge, and problems with strategies or tactics that inhibit performance of a system” (p. 126). These problems were addressed in one-on-one conversations with peers or with the research director, or as part of the regular group meetings, which also provided opportunities for students to gain experience presenting their work to other researchers. Stucky provides examples of how problem solving led to students’ gains in knowledge about how to do the different methods used in an organic chemistry research laboratory. However, few if any of the examples illustrate how students came to understand chemical processes, develop hypotheses, or analyze data needed to produce publishable results.

Nersessian and her colleagues engaged in a multiyear study of interdisciplinary science research laboratories (Nersessian, 2005, 2008; Nersessian, Kurz-Milcke, Newstetter, & Davies, 2003; Osbeck et al., 2011). This research is part of the large body of research on the cognitive practices of scientists that recognizes the importance of social, cultural, and physical environments (e.g., Dunbar, 1995; Giere, 1988; Tweeney, 1985). As such, Nersessian and her colleagues understand the laboratory as a cognitive-cultural system, where the laboratory is not conceived of as just the physical space, but rather as both the physical space including its artifacts, and the organized social group that makes up what we refer to in this article as the research group. It is within the laboratory as a cognitive-cultural system that the scientist is the acting person.
Nersessian and her colleagues see the scientist as engaged in model-based reasoning in the laboratory. They illuminate this most comprehensively in their 2011 book, *Science as Psychology* (Osbeck et al., 2011). However, their stated purpose of this book is to argue and demonstrate how a study of scientists at work can be used to inform the field of psychology. Therefore, while we find the analysis of science practitioners as problem-solving persons, emotional persons, and persons with professional and cultural identities informative, the most useful chapter in the book for our purposes is on the person as learner in the laboratory.

To Nersessian and her colleagues, laboratories are agentive learning environments with the following features:

- Requisite conceptual and methodological knowledge and skills are distributed, which enables everyone to make contributions, even undergraduate students.
- Laboratories are nonhierarchical—no one person is held up as the expert, even neophytes find niches where they can contribute expertise.
- Interactional structures afforded by the laboratory allow for the rapid identification of membership routes into the laboratory.
- Multiple social support systems foster resiliency in the face of the impasses and failures that are daily occurrences in this type of research (Nersessian, 2008, p. 72).

These features, according to Nersessian, provide the opportunity for apprenticeship learning.

As we noted above, Chapter 7 of *Science as Psychology* (Osbeck et al., 2011) is focused on the person as learner in the laboratory. It provides us with a case of one graduate student, A22, her role as a sensemaker in the laboratory and changes that occurred in her professional identity over a period of 6 months. A22 entered the laboratory with a background in mechanical engineering. Initially, she was given the task of culturing cells, which was the start of her “understanding cells' needs, processes, reactions, and possibilities” (p. 199). She learned to culture the cells by observing others, and then by doing it herself with coaching. As she worked with the cells, she became more proficient at keeping them alive and began to ask questions about how they are arranged in constructs. By mid-December, A22 had developed the ability to frame her own research, had a growing identity as part of the research community and with the field in general and its norms for significant work.

In this case, Nersessian and her colleagues provide us with a window into the learning that occurs as a new researcher begins working in a laboratory. In it, there is evidence of all of the features of an agentive learning environment and the learning opportunities associated with apprenticeships. However, as we noted above, we are only shown the first 6 months of what will eventually be for A22 a multiyear path to the Ph.D. Therefore, while it appears that in a few short months A22 has become a fully functioning member of the laboratory, she is still very much a learner. This can be seen in the March 2003 interview in which she was asked about her goals for the semester and year ahead. She spoke about wanting to learn laboratory techniques, such as histology, “burst pressure testing, mechanical testing, and live-dead testing” (p. 211). This is reminiscent of the findings from the studies of undergraduate research experiences reviewed above where students in UREs could become proficient in the technical skills of the laboratory but were unlikely to be able to develop research questions or to contribute to the field outside of the research group.

We feel it is also important to note that as with much of Nersessian’s recent work, this case is situated in laboratory science. In our work, we consider student participation in laboratory-based, field-based (Dodick, Argamon, & Chase, 2009), and computer-modeling research groups.
As we noted above, few studies have investigated the graduate education of new scientists. The studies reviewed above are three exceptions. A fourth is our work that we present in this paper and a previous one (Feldman, Divoll, & Rogan-Klyve, 2009). In that paper, we reported on our study of four science and engineering professors engaged in interdisciplinary research, each with his or her own research group. These are the same groups that we look at in this paper. That study relied primarily on our interviews of the professors about the ways that they educate their students to be researchers. It was supported by our observations of the groups and informal conversations with students.

In the previous paper, we noted that the research education of science and engineering students occurs as part of an apprenticeship and that the apprenticeship takes place in research groups. We saw that the research groups were organized in different ways, but they all had the characteristics of both communities of practice and epistemic communities. We now describe these aspects of research groups along with related literature.

**Apprenticeships.** We use the concept of apprenticeship developed by Lave and Wenger (1991): To be an apprentice is to engage in legitimate peripheral participation in a community of practice (COP). This engagement results in the situated learning of skills and knowledge needed to become an expert in the field. According to Lave and Wenger, all apprenticeships share common features. One is the indistinguishable nature of learning and the practice of work. A second is that the instructor partitions tasks into doable chunks for the apprentice that helps him or her develop new skills. Third, the apprentice demonstrates learning by accomplishing tasks in ways that are analogous to that of the expert (Lave & Wenger, 1991).

Anyone who has gone through the process of getting an advanced degree in the sciences or engineering will confirm that his or her experience was that of an apprenticeship. Berry (2000), in his reflective piece on graduate education in chemistry, described the experience in this way:

> The graduate student is probably as close to being a traditional apprentice as anyone in modern life. The graduate student works under the direction of a master, who guides and trains and, we hope, educates the apprentice until the student crosses the threshold of an advanced degree, normally the Ph.D. The student-apprentice has become a journeyman. (p. 30)

We saw the characteristics of apprenticeship learning in the studies reviewed above. For example, Bucher and Stilling (1977) wrote about how the graduate students learned by trial and error and help from others. Stucky (2005) described graduate students solving problems of practice supported by peers or the research director. Nersessian (2008) describes the laboratory as an agentive learning environment in which learning occurs as apprenticeships. That said, there is little in the literature that systematically provides evidence that the research education of new scientists has the characteristics of apprenticeships as described by Lave and Wenger (1991).

Our conception of apprenticeship learning is also informed by Collins, Brown, and Newman’s (1989) work on cognitive apprenticeships. In particular, we found the types of pedagogical methods associated with them useful: modeling, coaching, scaffolding, articulation, reflection, and exploration. In modeling, the instructor carries out a task so

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2It is important to note that engineering professors led two of the research groups that we studied. As engineers they sought to produce scientific knowledge that could be of use by practitioners in their fields—environmental engineering and hydrology. Therefore, we also refer to their groups as scientific research groups.
that the students can observe it and build a conceptual model of the processes needed to accomplish the task. Coaching is the process of observing students while they carry out tasks and providing them with hints, feedback, modeling, and new tasks that help them develop expert-like performance. Scaffolding consists of the supports like the suggestions and direct assistance that an instructor provides when coaching. The purpose of reflection is for students to compare their knowledge, reasoning, and problem-solving procedures with those of the instructor, other students, the research literature, or other experts. Exploration occurs when instructors encourage students to problem solve on their own. Articulation is when students express their knowledge, reasoning, or problem-solving procedures coherently.

Research Groups. The apprenticeship experience of students in the sciences occurs in research groups. Each consists of a lead researcher, a group of students and possibly postdoctoral fellows, and technical staff. The members do not necessarily work on the same research study. What defines the group are the area of study, and most importantly, the lead researcher, who is often a professor at a research university (Bucher & Stilling, 1977; Feldman et al., 2009; Osbeck et al., 2011; Stucky, 2005).

In our previous paper (Feldman et al., 2009), we reported that research groups can have different structures. We refer to them as being either loosely or tightly organized. It is important to note that we do not mean tightly or loosely coupled in the way that these terms are used in organization theory (Weick, 1976). For example, Weick (1976) uses the term “loosely coupled” to refer to events that are responsive to one another, but preserve their own identity and physical or logical separateness. He also suggests that loose coupling “carries connotations of impermanence, dissolvability, and tacitness all of which are potentially crucial properties of the ‘glue’ that holds organizations together” (p. 3). While research groups may have these characteristics, our use of the terms “loosely” and “tightly” refer to the possibility for interactions among members.

In tightly organized groups, the students and postdoctoral fellows associated with all of the lead researcher’s projects work together in shared laboratory space. Because of this, the laboratory serves as the center of action. The research groups studied by Bucher and Stilling (1977), Stucky (2005), and Osbeck et al. (2011) are examples of tightly organized groups. These groups meet on a regular basis to report on the progress of their research, share knowledge and skills, and critique one another’s research. They may also engage in the collective reading and critique of the literature in journal clubs (Golde, 2007). In addition to the formal discussions, the proximity of students, postdoctoral fellows, and the lead researcher in the laboratory provides for informal discussions. We also found that tightly organized groups engage in social activities together, such as cookouts and holiday and birthday parties.

In loosely organized groups, the lead researcher serves as the center of action. In this type of group, students work individually; for example, they do fieldwork, bring samples back to the laboratory where they are analyzed on communal instruments to quantify the data, and then work individually on their analysis. Rather than having group meetings, the lead researcher will meet with students individually to discuss their progress and provide guidance. Our research suggests that the way research is done in the scientific domain may determine whether a group is tightly or loosely organized. In our previous paper, we reported that the laboratory-based research groups we studied—microbiology and environmental engineering (biological processes)—were tightly organized, whereas the geochemistry group and the hydrology group, the former of which relied on individual fieldwork and the latter on the use of computer modeling, were loosely organized. Students in the tightly organized groups interacted more with other students than those in loosely
organized groups (see Figure 1). It also appears that how tightly or loosely organized the group is may depend on the personal characteristics of the lead researcher (Feldman et al., 2009). It also likely that the personal characteristics of the members of the research groups have an effect on the structure; however, we do not have data that look at this possibility.

Research Groups as Communities. Research groups have the characteristics of a COP (Lave & Wenger, 1991; Stucky, 2005). Wenger (2006) defines COP in this way: “Communities of practice are groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly” (p. 1). COPs have three crucial characteristics: (a) a shared domain of interest, (b) a group of people, called a community, that engages in “joint activities and discussions, help each other, and share information” (p. 2), and (c) “a shared repertoire of resources: experiences, stories, tools, ways of addressing recurring problems—in short a shared practice” (p. 2). To Wenger, COPs “are about knowing, but also about being together, living meaningfully, developing a satisfying identity, and altogether being human” (p. 134). For the COP to be all this, its members need to be able to participate in ways that allow them to hold some accountability to and for it. This requires an understanding of what the COP is all about, to be able to participate in it authentically, and to be able to shape what Wenger (1998) calls its enterprise. Finally, members need knowledge and ability in the COP’s practices to engage in it. Therefore, as COPs, research groups can be sites for learning the knowledge and skills required to participate legitimately in the enterprise of science using the repertoires of the science domain (Stucky, 2005).

One of the ways in which Wenger (1998) conceptualizes participation in communities of practice is as trajectories. To Wenger, a trajectory is not a fixed path; rather it is a “continuous

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3By skills we mean “the ability to use one’s knowledge effectively and readily in execution or performance” (Merriam-Webster Dictionary, 2011).
motion—one that has a momentum of its own in addition to a field of influences. It has a coherence through time that connects the past, present, and the future” (p. 154).

He describes five types of trajectories: peripheral, inbound, insider, boundary, and outbound. Peripheral trajectories allow for access to a COP, but never to full participation. Newcomers to the COP who have the possibility of becoming full participants follow inbound trajectories. As one would expect, they participate peripherally. Even when one is a full participant in the COP, roles, knowledge, skills, and identity change. They are following insider trajectories. Boundary trajectories are followed by participants who span boundaries and link COPs. Finally, there are trajectories that lead participants out of the COP (Wenger, 1998). Students enter research groups following peripheral or inbound trajectories. They also almost always follow outbound trajectories as they end their participation in the research groups. We use the idea of trajectories as we look at the experiences that students have as they participate in research groups.

Wenger (1998) also argued that COPs can serve as sites for the creation of knowledge. This knowledge can be of importance and reside only internal to the group, or it can be of broader importance external to the group. Wenger rightly argues that the latter could require “a reconfiguration of not only of their community, but also of their relations with other practices and of the economies of meaning in which they are to take new responsibilities for the meaning of what they do” (pp. 219–220). To do this, a COP must deal with the enterprises, styles, and discourses of other communities. For a research group, which by definition exists to construct knowledge that has more than local currency, the repertoire must contain those practices that make its enterprise acceptable more broadly. Therefore, it must have the characteristics of an (EC) (Creplet, Dupouet, & Vaast, 2003; Knorr Cetina, 1999) as well as those of a COP.

For our purposes, a research group is an EC in which its members—scientists, students, and others—have recognized expertise and competence in a domain of science and have an authoritative claim to knowledge within that domain (Haas, 1992). Given this definition, we see three characteristics of ECs that apply to research groups. First, members of research groups agree on what the central problems of their domain are. Second, they share beliefs about what makes responses to those problems valid. Third, they share normative and principled beliefs that provide a value-based rationale for their actions (Haas, 1992). This third characteristic is evident in scientists’ desire to create new knowledge in their field.

The creation of new knowledge in science is tied to recognition of expertise and competence. This is demonstrated through the attention that one pays to the field’s warrants for new knowledge. Because of this, members of ECs have a particular set of knowledge and skills that are used to create and warrant new knowledge. And because that knowledge must be warranted not only to the local group but to the field as a whole, they also must be aware of the implicit or explicit procedural authorities (such as the review panels for conference papers, journal articles, and funding proposals) that publicly acknowledge one’s expertise and authority.

The ways that the terms COP and EC are used in the literature suggest that they refer to actual groups of people. We see the notions of COP and EC as theoretical constructs that can be used to understand groups of people. Therefore, we can allow for a research group to have both the characteristics of a COP and the characteristics of an EC. As we discuss later in this paper, members of the research group can be engaged in research in ways that suggest that they are members of a COP or members of an EC, or both, depending on their roles in the group.

It should be clear from our conceptualization of research groups as having the characteristics of both communities that we are concerned with how learning to do research occurs within cognitive, social, and cultural milieu. As Nersessian (2006) argued and
demonstrated about laboratories, we see all science research groups as being complex cognitive-cultural systems. We draw upon this in the analysis of the research groups that we studied.

METHODS

The focus of our research is how one learns to be a scientist while participating in a research group and how this changes as one progresses through a degree program. In this paper, we focus on the ways in which the science and engineering students experienced their research education. The setting for this study was a National Science Foundation (NSF) funded interdisciplinary collaboration among geologists, microbiologists, environmental engineers, and science educators to study the natural remediation of acid mine drainage (AMD) at an abandoned pyrite mine. The project had five PIs, all of whom were professors at a large, public, research-intensive university. Four of the professors were scientists or engineers. Each oversaw a research group that included undergraduate, masters’, and doctoral students, as well as practicing middle or high school science teachers. The fifth professor does research in science education and is one of the authors of this paper. He, too, has a research group, which includes the two coauthors of this paper.

Although we collected a wide variety of data, our study relies primarily on the students’ perceptions of their experiences as members of research groups. Therefore, we see our study as taking a phenomenological approach based on interviews and triangulated with the data from the other sources described below. We use the following definition of phenomenology:

Phenomenology is a . . . theoretical point of view that advocates the study of direct experience taken at face value; and one which sees behavior as determined by the phenomena of experience rather than by external, objective, and physically described reality. (Cohen & Manion, 1994, p. 29)

In this approach, we focused on the experienced world that our participants—science and engineering students—take for granted (Schutz, 1967). Because we were concerned with their experience and how they made meaning of it, rather than how they behaved, our primary form of data collection for this study was interviews with students (Seidman, 2006).

Data Collection

The data reported here are part of a larger data set that include three forms of data collection: interviews of the PIs’ undergraduate and graduate students, interviews of the PIs, and participant observation in research seminars and project meetings. We selected the students to interview in such a way as to have at least two students from each of the four research groups lead by the PIs, and at different points in their studies. We also tried to include different levels of students, that is, undergraduate, master’s, and doctoral students (see Table 1). Our interviews used broad, open-ended questions to build upon and explore the students’ responses to the questions. In this way, we helped the students to reconstruct their experiences and to relate them to us. During the interviews, we asked questions that followed up on the students’ responses to help fill out their answers and to check our understanding of their experiences (Seidman, 2006). Each of the 10 students was interviewed for approximately 60 minutes. We recorded interviews and observation data as notes and audiotapes. All interviews were transcribed. For the purpose of this study, we only drew upon the student interviews and fieldnotes. The PI interviews were used in our
TABLE 1  
Student Participants

<table>
<thead>
<tr>
<th>Name</th>
<th>Status</th>
<th>Research Group</th>
<th>Type of Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ajay</td>
<td>Doctoral student</td>
<td>Sarah</td>
<td>Tightly organized</td>
</tr>
<tr>
<td>Amisha</td>
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<td>Douglas</td>
<td>Loosely organized</td>
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<td>Celia</td>
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<td>Charlotte</td>
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<td>Deana</td>
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<td>Elena</td>
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<td>Jodi</td>
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<td>Paul</td>
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<td>Raymond</td>
<td>Master's student</td>
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<td>Sanghe</td>
<td>Doctoral student</td>
<td>Sarah</td>
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earlier work and here were used as needed to further explain the students’ situations and comments (Feldman et al., 2009).

**Data Analysis**

We analyzed the interviews using the methods of the phenomenological analysis of interview data (Hycner, 1985). After transcribing the interviews, we bracketed the data. That is, as much as possible we suspended our meanings and interpretations of the data and instead attempted to enter into the students’ worlds (Hycner, 1985). We then reviewed the interviews to seek what Hycner (1985) calls “units of meaning” to elicit the students’ meanings “expressed in a word, phrase, sentence, paragraph or significant non-verbal communication” (p. 282). Units of meaning, which are derived from the students’ literal words, are unique, coherent, and are clearly delineated from the rest of the interview. Using the themes that emerged from the interviews, we each coded the fieldnotes to further look for patterns and themes. We eliminated redundancies, clustered the remaining units of meaning, and checked them as much as possible with the students we interviewed. Rather than calculate interrater reliability, we individually coded the data from several sources and then discussed our coding choices. This clarified differences among our meanings of the codes and helped us to apply them consistently. The clustered units of meaning were then examined to identify the themes for our findings. Furthermore, we identified a list of the most frequent methods of cognitive apprenticeship and by whom they were initiated (professor or student) (see Figure 2) and the methods of cognitive apprenticeship that occurred in the different types of research group (loosely organized or tightly organized) (see Figure 3). From this process, we identified three students who typified the common themes reported in this paper. Thus, we decided to use the experiences of these students to highlight the patterns we found. We were influenced by the methods of grounded theory (Corbin & Strauss, 2007), which we have used in previous studies. We also used the methods of Miles and Huberman (1994) for the graphical organization of qualitative data, as in Figures 1–3. The vignettes that we develop of three students (Paul, Jodi, and Celia) draw upon case study methods (Yin, 2009). Throughout this process, we used the qualitative analysis software HyperResearch to help us with our analysis.

**FINDINGS**

Our intent in this study was to better understand what it is about the students’ participation in the research groups that leads to their ability to engage successfully in scientific research.

and how this changed as they progressed through their degree programs. While there is
general agreement in the field that students participate in research groups as apprentices,
there is little research that supports this belief (Sadler et al., 2009). In what follows, we
provide evidence that the students are in the role of apprentices, although neither they nor
their professors make that explicit. As apprentices, they learn by doing as legitimate periph-
eral participants (Lave & Wenger, 1991) as they engage cognitively and culturally (Osbeck
et al., 2011) in the groups. Mentoring is distributed among the group, with more advanced

students contributing to it. Finally, because the research groups are both communities of practice and epistemic communities, students’ expertise grows along two dimensions as they gain methodological and intellectual proficiency.

While we draw on data from all the interviews, we focus on three students in particular and provide vignettes of their experiences in the research groups. Providing a rich description of three students provides a more in-depth characterization of the typical student research-group participation we found among the students in our study. We also focus on these three to help provide an image of the progress through the Ph.D. process. One was an undergraduate honor’s student in a loosely organized group (Paul). The second was a master’s degree student in a loosely organized group (Jodi). The third was a doctoral student in a tightly organized research group (Celia). We selected Paul, Jodi, and Celia from three different research groups because they represented the three different levels of students in the groups—undergraduate, master’s, and doctoral. They also represent both types of research groups—loosely and tightly organized.

The Research Groups

Celia was a doctoral student in Karl’s tightly organized microbiology research group. All of his graduate and undergraduate students, as well as any postdoctoral fellows, work together on a daily basis in his laboratory. Celia told us that Karl’s research group is a place where “you talk to people. You learn what they do. You see how people set up their own instruments” (Celia interview). Karl’s research group meets weekly, and students are expected to make regular presentations about their work and hold group discussions. During at least one semester each year Karl has his students participate in a journal club that meets once per week for 1–2 hours. Journal clubs are “formally organized reading groups that discuss an article found in the recent research journals. A single article is at the heart of each journal club presentation and discussion; the articles under discussion are ones deemed scientifically important” (Golde, 2007, p. 345). In addition, Karl holds community-building events such as cookouts, dinner parties, and birthday parties.

Jodi was a master’s degree student in Robert’s loosely organized geology research group. Robert works with students on an individual basis rather than as a group. His students do fieldwork, bring samples back to the laboratory where they are analyzed on communal instruments to quantify the data, and then they work individually on their analyses. In his case, while there is a laboratory, it is not used as a place where the group congregates to do work. Jodi described her lab experience in this way: “Our lab was pretty small. There weren’t a lot of people using it. . . . Usually I was the only one in there” (Jodi interview). For the most part, Jodi interacted with Robert on a one-to-one basis about every other week. She told us that she rarely interacted with the other professors in the AMD project. There were two types of situations in which Jodi interacted with other students. Once a month, she organized trips to the field site to collect samples, and because she was in charge of two of the analytical instruments, other students frequently came to her to have their samples analyzed. She was the only one of Robert’s students who had multiple connections with other students.

Paul was an undergraduate doing an honor’s project in Douglas’ research group. Douglas is a hydrologist who primarily does modeling of hydrological systems. His research group is loosely organized. Like Robert, Douglas usually meets with his students on a one-to-one basis, which he did with Paul on a weekly basis. As an undergraduate doing an honor’s project, Douglas teamed Paul with one of his doctoral students, Amisha. Paul helped Amisha do some fieldwork and model the data that they collected. As a result, there were frequent meetings and daily phone calls between Paul and Amisha. Paul told us that although he
was aware that Douglas has other students, “I don’t work with any of them on my portion of the project, it’s just [Douglas] and Amisha” (Paul interview).

Although we do not focus on a student from Sarah’s research group, it is important for us to describe it at least briefly. Sarah, who is a professor of environmental engineering studying biological processes, had a tightly organized group. Like Karl, her students participated in journal clubs. They also shared lab space and had social gatherings initiated by Sarah.

From these brief descriptions of the research groups, it should be evident that they exhibit the features of agentive learning communities (Nersessian, 2008). As we will see in more detail later in the paper, the knowledge and skills needed to do research were distributed among members of the research groups. There appeared to be little hierarchy among the students. However, as would be expected, the professors had more power than the students given that they were the students’ advisors, employers, and provided the research groups with their overall goals. Participants had a wide variety of ways to interact with one another, with the tightly organized groups providing more opportunities with their lab settings, regular group meetings, journal clubs, and social events. There were also multiple support systems available to the students, with the tightly organized groups again providing more.

The Research Groups as Sites for Apprenticeships

We now take a closer look at participation in the groups to demonstrate how they were sites for apprenticeship experiences. We again rely on data from our interviews of these three students, but also supplement it with data from interviews of other students.

Other than general courses on instrumentation or statistics, none of them learned to do these procedures as part of coursework. Rather, they learned what to do by being engaged in their work. According to Lave and Wenger (1991) this is one of the more important features of apprenticeships. We already saw this in Celia’s description of Karl’s research group. She also told us,

The technical skills, I learned through my research experience. I learned to use an ICP (Inductively Coupled Plasma Spectrophotometer). I learned how to put bottles, sediments and things like that together, and how to measure this component versus that component.
(Celia interview)

Similarly, Raymond, a master’s degree student in Robert’s group, told us that he learned to do research by doing research: “Most of the stuff I just kind of picked up along the way. I mean, in terms of the instruments and analysis I use, I’ve just kind of learned them as I needed to” (Raymond interview).

Although the students were aware that they learned to do research by doing it, they tended to be unaware that the others (their professors and other students) who helped them to learn were proactively teaching them to do research. For example, Elena, a doctoral student in Sarah’s group, told us “I don’t know if somebody really teaches you how to do research (Elena interview).” The lack of awareness by the students that they were being taught to do research is also consistent with the nature of apprenticeships. According to Lave and Wenger (1991), the nature of learning in an apprenticeship is indistinguishable from the practice of work. It is also characterized by the “instructor” partitioning tasks into chunks that are doable by the apprentices. We saw that as part of the mentoring done by the professors and by other students. The professors in our study mentored all of their students by conducting formal and informal meetings. For example, Jodi, a master’s
student, described how Robert helped her to gain the skills needed to analyze the data that she collected: “I’d say, ‘I have no idea how to look at this data.’ And he would suggest different types of graphs I could make that would help me look at the data and identify the trends” (Jodi interview). Paul, an undergraduate, also received guidance from his advisor: “He’ll like point me in the right direction for articles on how to do experiments and how to set up experiments. He’ll be like, ‘Maybe you should find out what other people have done in the area’” (Paul interview).

Students also mentored other students. For example, Celia told us how she mentored an undergraduate: “I like treating her like, like she’s my mentee. I give her a lot of tips on how to stay organized, and how to design a project” (Celia interview). Paul described how his expertise grew when working with Amisha: “So, we’ll think about why didn’t it work, how can we fix it, and together we’ll come up with better ways of sampling, or better ways of recording data” (Paul interview).

Although we call this type of interaction between students mentoring, it appears to be different from the way in which the professors mentored them. The differences can be seen when the types of interactions between professors and students and students and students are classified into the different pedagogical methods of cognitive apprenticeships (Collins et al., 1989): modeling, coaching, scaffolding, articulation, reflection, and exploration. Figure 2 shows the frequency of these methods identified in the student interviews according to whether the professor or other students initiated them. The data show that professors urged students to explore about twice as often as did other students. The professors were more likely to give the student tasks or projects to do and to help them to achieve them by giving advice that made the tasks doable. The biggest difference is in articulation. We have no evidence that students helped other students to articulate their knowledge, reasoning, or problem-solving procedures.

We also looked to see the ways in which the different models of cognitive apprenticeships appeared in the student interviews according to whether the student was in a tightly or loosely organized research group (see Figure 3). As Figure 1 shows, students had more opportunities to connect with other students in the tightly organized groups like Karl’s and Sarah’s than in the loosely organized groups like David’s and Robert’s. We wondered whether this could have an effect on the ways that students referred to interactions that corresponded to different methods of cognitive apprenticeship. We found that students in the tightly organized groups reported a higher frequency of modeling, scaffolding, reflection, and exploration than those in the loosely organized groups. There was roughly the same amount of articulation, with more coaching in the loosely organized groups. When comparing Figures 2 and 3, one can see that it is not surprising that the articulation was the same for both types of groups. That is because all of the articulation happened between faculty and students. Therefore, we would not expect to see an effect of student–student interactions.

In modeling, the person in the instructor role carries out the task so that the learner can observe it. In the tightly organized groups, this is more likely to happen because students observed one another and the professor in the laboratory setting. The interviews of the students in loosely organized groups suggest that most of their meetings with their professors occurred in offices, where they would less likely be able to observe research methods. In coaching and scaffolding, the learner is offered feedback to help improve his or her performance. When the two categories are combined, there are nearly equal numbers of instances in both types of groups. There were more than twice as many instances of reflection in the tightly organized groups than in the loosely organized one. This is not surprising because students in the former have opportunities to reflect with each other as well as with their professors. They also had regular group meetings, including journal clubs,
The professors encouraged their students to reflect. The students in the tightly organized groups also referred to a higher number of instances we coded as exploration than did the other students. While this may be due to the difference in the group structures, it could also be due to the differences between laboratory-based science on the one hand, and field-based and modeling-based science on the other. Again, it is important to point out that while Collins et al. (1989) refer to this as a cognitive apprenticeship, it is best seen as a cognitive-cultural process that includes interactions among people (student–student, student–professor) and with the materials and tools of the research groups.

The Growth of Expertise

One of the goals of our research is to better understand the learning trajectories of the students’ participation in research groups. Our research suggests that as students participate in the research groups, they gain two types of proficiency—methodological and intellectual—and that as they gain proficiency, their roles in the groups can change from novice researcher to proficient technician to knowledge producer. It is important for us make clear that we do not have the longitudinal data that can illustrate the gain of either type of proficiency or change in roles of individual students. However, we can show what this growth looks like by comparing students at different levels in their academic trajectories: Paul (undergraduate), Jodi (master’s degree student), and Celia (doctoral student). We do note that Paul and Jodi were members of loosely organized groups and Celia a member of a tightly organized group. Given that our intention here is to illustrate what different levels of proficiency look like rather than what caused the students to have these levels at the time of the study, we believe that the difference in the structure of their groups is not an important factor.

Methodological Proficiency. Paul was beginning his senior year when he joined David’s research group. At that time, his only research experience was in the laboratory, field, and design courses that he took as a civil engineering major. He possessed few research skills that were specific to the study of the hydrology of the AMD site. As a result, his main goal for his work in the research group was to learn specific techniques, use them to collect data, and report the data in his honor’s thesis. He told us “In order to finish [my honor’s project] I’ll have the three tests: the tracer test I’ve already done, the velocity test, and the groundwater test” (Paul interview). As it turned out, he accomplished much less than his goal, having only completed the tracer tests, but was able to demonstrate in his honor’s thesis that he had enough methodological proficiency to satisfy Douglas’ expectations for an undergraduate student.

Jodi also joined her research group with little in the way of research skills. But while Paul’s tenure in his group was limited by the constraint of his graduation date, Jodi, as a master’s degree student, remained a member of Robert’s research group until she completed and defended her thesis. By the end of her studies, Jodi had become the AMD project’s methodological expert in two areas. First, she was in charge of and responsible for all the analysis done using the major instruments in Robert’s laboratory: the ion chromatograph (IC) and the inductively coupled plasma mass spectrograph (ICP). It was the work with these instruments that she described in her typical day. Second, she was responsible for the field trips to gather water samples from the wells drilled at the AMD site and made sure that the proper protocols were used to collect, store, and analyze the samples.

These terms were suggested to us by the professors (Feldman et al., 2009).
Although Jodi had expertise in these two areas, we saw little evidence that she made significant changes in the protocols or developed new methods. In short, she became an expert in the methods that she was expected to do as a master’s degree student in line with Robert’s view of how a master’s student with Jodi’s experience could contribute to the research group.

Celia brought with her the skill set that she learned while getting her master’s degree. In Karl’s laboratory, she learned new techniques: First to carry out the analyses that Karl needed, and then others that she found she needed to carry out her own research. These included fluorescent in situ hybridization (FISH), polymerase chain reaction (PCR), and sulfur isotope analysis. In addition, she modified techniques and developed new ones as she searched for and tried to identify the strains of bacteria at the AMD site. As she told us: “You know, I keep searching for these bugs [bacteria]. I tried different methods, different angles, and some of them are inconclusive, so I have to try another approach” (Celia interview). Celia is skilled at data analysis and interpretation; she transfers established techniques to novel situations and exhibits enough familiarity with research and research methods that she is able to develop new techniques for application in novel situations. She has considerable experience to draw on and can use published methodologies in addition to innovating new ones.

What we see in these students are three different levels of methodological proficiency. Paul, as an undergraduate honor’s student, learned a particular skill set that allowed him to gather and analyze the data to Douglas’ satisfaction. Jodi learned a wider range of methods, and because of her expertise in using the IC and ICP, she oversaw their use and taught other students how to use them. In addition to the types of skills that Paul learned, Jodi developed proficiency in managing research and mentoring other students. In Celia, we see more methodological proficiency. In addition to being able to use published methodologies and mentor other students in their use, she has the ability to be innovative and develop new methods. The differences in methodological proficiency among Paul, Jodi, and Celia are similar to the changes that one would see in apprentices as their participation becomes less and less peripheral to the work of the research group (Lave & Wenger, 1991).

**Intellectual Proficiency.** It is not clear from our data that Paul developed the ability to formulate research questions. In fact, it is not even clear that he knew the research question he was trying to answer as he worked with Amisha, a doctoral student in Douglas’ group. When asked what his research project was, he told us, “I’m working with Amisha who’s doing some of the modeling and giving her the kind of velocity and hydraulic data, and she’s using that to help her modeling” (Paul interview). In his honor’s thesis, Paul described his research methods and presented his data without the type of analysis that would suggest the ability to draw defensible conclusions from his data. Nor did he demonstrate that he could create, disseminate, or defend new knowledge. In short, he demonstrated little intellectual proficiency. This is not surprising given his short-term tenure within the research group, his being an undergraduate, and the expectations of an undergraduate in Douglas’ research group.

Jodi told us that her research was to “interpret the extent of contaminated ground water and surface water” (Jodi interview). Her advisor, Robert, gave her the project:

> Having never done a project like this before, I asked him what he needed done. And he said, “Well we have this grant, we need people to go out and collect samples of surface water and ground water.” And he would do something with that data, like look at it. And so basically the project turned into a larger version of what we found, which was basically
looking at the concentrations, how they change seasonally, over time, and how they change spatially between the different wells. (Jodi interview)

Jodi saw two purposes for her research. One was to produce the thesis that was required for her degree program. The other was to supply data to Robert and to the microbiologists in Karl’s research group:

I thought that it would be used by other researchers, particularly the microbiologists. They were going to take the data I collected . . . to say, “this is what the water chemistry is like, and these are the bacteria that I find in, living in that water.” . . . And I was the one that was going to tell them the water conditions. (Jodi interview)

After she completed her master’s degree, a geotechnical engineering consulting firm hired Jodi. At the urging of her employers and with help from Robert (Robert, personal communication), she prepared a manuscript about her research that was published in a regional geosciences journal.

Clearly Jodi is more intellectually proficient than Paul. She was aware of her research question and that of the larger project. She was able to draw conclusions from her data and to defend them to her thesis committee. However, she did not see her data and analysis as something that would become part of the literature of the field, but rather would remain within the AMD project to be used by others. This suggests that she did not see herself as being part of the larger EC. Even though she eventually published her master’s work, she did so to satisfy her employer’s request rather than as a contribution to the knowledge base on AMD (Robert, personal communication).

At the time of our interview of Celia, more than 2 years before she expected to complete her doctorate, she exhibited most of the characteristics of intellectual proficiency. She was able to formulate her own research questions based on work previously done under her advisor, articulate her research question, and was aware of how her questions were situated within the broader questions of the AMD project. She used published literature as a source for ideas and as a context for current research and was skilled at drawing defensible conclusions from data. Celia was aware of the larger EC and contributed to the knowledge base on AMD by presenting her work at conferences. Her future plans included submitting papers to journals, and in fact, it is a requirement of her degree program that she have at least three publications to graduate.

Celia was very clear about her research: “my project involves quantifying the microbial contribution to the attenuation of acid mine drainage through measuring sulfate reduction or iron reduction” (Celia interview). Celia was one of the few students that we interviewed who was explicit about the need to have data to support her conclusions. She told us that

We see in our preliminary studies that sulfate reduction is happening. We find some evidence of it, right. But you still need to find the microbe. I still need to study that microbe and what it’s doing in the environment, because whatever else we see in that environment also can be causing the reduction as well as the microbes. (Celia interview)

She was also aware that her goal was to become part of the EC. She said that she wanted to contribute to the field of microbiology and that she expects her work to be published. When we asked her what she thought the product of her research would be, she responded,

It will be published. Of course I intend to go to national meetings like ASM (American Society for Microbiology), and I’m actually going to be presenting there a poster and

give a talk for the second time. . . . [Also] AGU (American Geophysical Union) or GSA (Geological Society of America), they have some acid mine drainage subdivisions within their conferences. (Celia interview)

As can be seen, Celia not only has the goal of being published, she has knowledge of the procedural authorities in her field.

Our three cases show a wide range of methodological and intellectual proficiency. Paul began his senior year with little in the way of methodological or intellectual proficiency for scientific research. Although he developed knowledge and skills in both areas by the time he graduated, he participated in the COP, but not the EC within Douglas’ research group. As such, Paul exhibited the qualities of what the professors referred to as a novice researcher (Feldman et al., 2009). Novice researchers are newcomers to the group who have little or no experience with scientific research. As they engage as legitimate peripheral participants (Lave & Wenger, 1991) in the research group, they develop the skills to collect data and to maintain the laboratory, field site, or other equipment. The professors that we interviewed believed that novice researchers do not have the ability to formulate research questions, that they lack research skills, and that they have difficulty drawing defensible conclusions from data. As a result, they are not expected to contribute much if anything to the analysis of data or the creation of new knowledge (Feldman et al., 2009).

Proficient technicians are generally longer term members of the group and therefore had the opportunity to develop the skills needed to collect and analyze data, and to report results to other researchers. However, we saw that professors did not expect them to be adept at developing research questions. They were expected to have the research skills that allowed them to do what is necessary for the research project and could apply the methods that they have learned to new situations (Feldman et al., 2009). Proficient technicians have the knowledge and skills necessary to become skilled practitioners in their field.

During the course of her two-and-a-half years participating in Robert’s research group, Jodi developed from a novice researcher to a proficient technician. She became an expert in the methods she used in the laboratory and in the field. She gained enough intellectual proficiency to be able to analyze and report on her data to the other researchers in the AMD project. She participated as a member of the COP within Robert’s group and peripherally in the EC. In all ways she was an expert proficient technician. We saw something quite different with Celia. She had a high level of methodological proficiency, and her intellectual proficiency was such that she was on the edge of becoming a full participant in the EC. We therefore saw her on the verge of being a full-fledged knowledge producer.

To the professors we interviewed, knowledge producers are able to formulate their own research questions, develop new research methods, and add to the research literature. In our examination of how methodological and intellectual ability grows through participation in research groups, we did not consider whether the students were part of tightly or loosely connected groups. It may appear that Celia was the only student who exhibited levels of proficiency similar to those of an expert because she was in a tightly organized group rather than a loosely organized one. However, there are members of both types of groups that achieve this as indicated by their completion of the doctoral degree and their later success as independent researchers. Similarly, there are members of tightly connected groups who end their formal education at the master’s level with the level of expertise of a proficient technician. This was not at all uncommon among Sarah’s students because of the opportunities in industry for students with master’s degrees.
**Communities of Practice and Epistemic Communities**

We now return to the distinction that we made earlier between communities of practice and epistemic communities and how that relates to methodological and intellectual proficiency and to roles within research groups. The research groups that we examined in this paper have the characteristics of a COP. They each have a shared domain of interest that are broadly defined by their scientific discipline and more tightly defined by their research questions. They are communities that engage jointly in research activities, helping each other, and sharing information about their research interests. The members of the research groups are practitioners, engaged in the practice of science. Also, we saw that they are sites for learning the knowledge and skills required by the students to participate legitimately in the enterprises of their scientific disciplines.

As we noted earlier, Wenger (1998) argued that COPs can be sites for the creation of knowledge. Our data suggest that research groups, as knowledge-producing epistemic communities, can serve as the sites for the growth of intellectual as well as methodological proficiency. This was especially apparent in Celia’s case. The type of intellectual proficiency that she was gaining was in response to the need to warrant her research so that the wider scientific community would accept it. Paul and Jodi, who produced findings for use by their research groups, did not gain the knowledge and skills needed to be full participants in the EC.

**DISCUSSION**

Our goal for this study was to come to a better understanding of what it is about students’ participation in research groups that leads to the ability to engage in scientific research. We also sought to be able to present at least the beginnings of a comprehensive model for understanding the learning trajectories of students from their first entry into a research group to the attainment of their degrees. Our model begins with the acknowledgment, described by others (e.g., Bucher & Stilling, 1977; Osbeck et al., 2011; Stucky, 2005) and supported by our data, that the students participate in the research groups as apprentices. The students, as legitimate participants in the research groups, learn by doing, by interacting with peers and mentors, and by interacting with the materials and tools needed for research in their field. The student learning is facilitated by the nature of the research group as an agentive learning environment. The types and frequencies of interactions are related to the structure of the research groups as either tightly or loosely organized. This structure affects the research group as a cognitive-cultural system. We saw in the research groups that we studied that the students developed methodological and intellectual proficiency. As their proficiencies grew, their participation became less peripheral and more integral to the functioning of the group.

Our representation of this model can be seen in Figure 4. Before describing it, we want to note that this diagram does not begin to accurately represent the complexities of student learning by participation in research groups. However, we do believe that it contains some of the more salient features. We represent the research group by the largest oval. The dashed line suggests the porous nature of its boundaries. Participants, materials, tools, knowledge, and skills flow in and out of it. The large oval is divided in two with the left representing those aspects of the research group that have the features of a COP, and the right those features of an EC. In this case, the line is dashed because there is no boundary between the two types of communities. The research group is a cognitive-cultural system with characteristics of both COPs and ECs. However, students can be participating in the
research group in such a way that is more or less like one or the other, hence the division into COP and EC areas.

On this representation of the research group, we have drawn lines that suggest possible learning trajectories for Paul, Jodi, and Celia. Paul’s is what Wenger (1998) called peripheral. As an undergraduate, he entered the research group and left rather quickly with no expectation that he would ever be a full participant in the group. We have his trajectory only passing through the left side of the group because he experienced it primarily as a COP and gained methodological proficiency. He left the group as a novice researcher.

We see Jodi’s learning trajectory as being inbound and outbound. As a master’s degree student, she certainly had the possibility of becoming a full participant in the group. However, her time in the group, represented by the circle on the left, was mostly involved with what we have called the methodological aspects of research. Therefore, her trajectory stays to the left, which is indicative of the limited growth of her intellectual proficiency. Her trajectory is also outbound, because she left the group, at the completion of her masters’ studies, as a proficient technician.

Celia, like Jodi, has a trajectory that combines inbound and outbound trajectories. However, we believe that she also experienced an insider trajectory as a full participant of both the COP and EC aspects of the research group. Therefore, we have an oval for her trajectory that includes the COP and EC aspects of the research group, representing the growth of both her methodological and intellectual proficiencies. She, too, leaves the group, but only after gaining the knowledge and skills needed to participate in the wider EC of her field as a knowledge producer.

**IMPLICATIONS AND CONCLUSION**

Our ultimate purpose in doing this research is to use our findings to improve science teaching and learning. Therefore, we conclude our paper with implications for the design of research experiences. We begin with the type that we studied, relatively long-term
participation in ongoing research groups as part of degree programs. Our findings suggest that it is important for professors to acknowledge explicitly that their students are in the role of apprentices and that as apprentices their working experiences are also the primary mechanisms for them to develop methodological proficiency. Our findings also suggest that there is need for professors to be more proactive in helping their students gain intellectual proficiency not just as part of doctoral studies but also for undergraduates and master’s degree students. Journal clubs are one way to do this, but we believe that much can be gained by the planned use of the methods of cognitive apprenticeship (Collins et al., 1989) to help students to learn the epistemic aspects of doing science. In addition, the professors need to recognize the important role that peer mentoring plays in the research lab and consider training students to improve the outcomes of these relationships. The components of the cognitive apprenticeship, i.e., modeling, scaffolding, articulation, reflection, and exploration, provide a frame for such training. Finally, our findings suggest that tightly organized research groups can be more fertile ground for learning than loosely organized groups. Although the former are more likely to be maintained in the laboratory-based sciences, it is possible to hold regular research group meetings, have journal clubs, and arrange social functions in any science domain.

We also believe that our findings have implications for short-term research experiences like the NSF-funded Research Experiences for Undergraduates (REU) and Research Experiences for Teachers (RET). Our study of an REU program (Feldman & Özalp, 2012) found that, for the most part, undergraduates like Paul gained some methodological proficiency but little in the way of intellectual proficiency. This also appears to be the case for the students in the Kardash (2000), Rauckhorst et al (2001), Lopatto (2004), and Laursen et al. (2010) studies.

As we saw in this study, when participants are placed in ongoing research groups, the type of research group can have an effect how their methodological and intellectual proficiency grows. We saw that in tightly organized research groups students can have several mentors in addition to their professors. These research groups are often made up of students who have different methodological and intellectual proficiencies and are in different roles. Novice researchers can benefit from being in frequent contact with proficient technicians, and proficient technicians are mentored by the growing expertise of the advanced doctoral students as they became knowledge producers. This is much less likely for the students in loosely organized research groups. They infrequently had contact with more advanced students, and, for the most part, they relied solely on their professors as their mentors. This suggests that in research apprenticeship programs for novice researchers, such as undergraduates and teachers that rely on placements in ongoing research groups, the participants will likely benefit more from being immersed in a tightly organized group. The major drawback with this suggestion is that not all domains of science organize their research groups in this way. In addition, our data suggest that the dispositions of the professors is also a factor. Simply put, those who are more social are more likely to organize the formal and informal meetings that help the group members bond in ways that promote mutual mentorship. Another factor that influences students’ involvement in the research group is the professor’s expectations for them based on their levels as undergraduate, masters, and doctoral students (Feldman et al., 2009). Therefore, the type of research group, the dispositions of the leader of the group, and expectations for the undergraduates and teachers can influence how methodologically or intellectually proficient undergraduates and teachers become.

Our research also suggests that it is important to have realistic learning goals for the undergraduates and teachers who participate in short-term research experiences. It is unlikely that in 4–10 weeks a novice researcher will gain the methodological and intellectual proficiency expected from such short-term experiences.
proficiency needed to become a knowledge producer fully participating in an EC. We do believe that it is possible, through the incorporation of formal learning opportunities, for students and teachers to gain the methodological proficiency to complete a small, well-defined research project, and for them to gain an understanding of the ways in which a research group works as an EC. Learning opportunities, such as weekly seminars and journal clubs (Golde, 2007), can be used to help students learn how to identify and construct researchable questions, how to search and read the literature for appropriate knowledge, and how knowledge is warranted in the field.

We also found that among the students in our study, the engagement in the EC grew slowly as they gained in intellectual proficiency. As with all apprenticeship learning, this occurs through doing—in this case by writing proposals and papers, critiquing the work of others, and attending and presenting at conferences. It is facilitated by close mentoring by professors as they read and comment on their students’ work. This suggests the need to have modest epistemic goals for short-term research experiences. It may also suggest the need for explicit instruction in the epistemic aspects of the nature of science (e.g., Schwartz et al., 2004).

In our introduction to the paper, we referred to the calls for teachers to teach science as inquiry and to teach students how to do research. We end by speculating, based on our findings, if there is a viable place for research experiences in formal K-12 education.

Inherent in all apprenticeship models is the presence of “masters,” those members of the COP who have expert skills and knowledge. If research apprenticeships are to take place in K-12 schools, then there need to be those who can serve in that role. It seems unlikely that many science teachers can do this because of their limited participation in authentic science. For them to serve as the masters, they would need to have the opportunity to participate legitimately in scientific research. Unfortunately, few teachers have had the opportunity to do so as undergraduates and the numbers who have the opportunity to participate in RETs is also small. In addition, our study suggests that the most we can expect teachers to gain through traditional short-term research apprenticeships is the methodological proficiency of a proficient technician and some understanding of the epistemic functions of a research group. However, this may not be enough if they are expected to be the “masters.”

This suggests that if we want all students to have the opportunity to engage at some point in research experiences as part of their formal schooling, then science teachers need to gain the methodological and intellectual proficiency necessary to adequately mentor their students in these experiences. We believe that this can be facilitated by structuring RETs so that they are placed in tightly organized research groups with mentors who explicitly teach them how to do science.

REFERENCES


