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Facilitating Collaborative Knowledge Building

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This article describes a detailed analysis of knowledge building in a problem-based learning group. Knowledge building involves increasing the collective knowledge of a group through social discourse. For knowledge building to occur in the classroom, the teacher needs to create opportunities for constructive discourse in order to support student learning and collective knowledge building. In problem-based learning, students learn through collaborative problem solving and reflecting on their experiences. The setting for this study is a group of second-year medical students working with an expert facilitator. The analysis was designed to understand how the facilitator provided opportunities for knowledge-building discourse and how the learners accomplished collective knowledge building. We examined episodes of knowledge-building discourse, the questions and statements that the students and facilitator generated throughout the tutorial, the change in their understanding of the problem that they were solving, and the collective knowledge that was constructed. The results indicate that the group worked to progressively improve their ideas through engaging in knowledge-building discourse. The facilitator helped support knowledge building through asking open-ended metacognitive questions and catalyzing group progress. Students took responsibility for advancing the group's understanding as they asked many high-level questions and built on each others thinking to construct collaborative explanations. The results of this study provide suggestions for orchestrating knowledge-building discourse.

The goal of many constructivist learning environments, such as problem-based learning (PBL) (Barrows, 2000), is knowledge building. Knowledge building is

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generally viewed as a discursive activity intended to enhance collective understanding (Bereiter, 2002). It requires that participants take responsibility for learning what they need to know as they become engaged in "the collaborative solution of knowledge problems in such a way that responsibility for the success of the effort is shared by the students and teacher instead of being borne by the teacher alone" (Scardamalia, 2002, p. 77). But how does such knowledge building proceed and how might a teacher support knowledge building discourse?

Our goal in this article is to characterize the knowledge building that occurs in a PBL tutorial. Specifically, we provide a fine-grained analysis of a successful tutorial engaged in by a group of medical students, working with a highly skilled facilitator. We examine the nature of the questions that are asked, the discourse that ensues, and the evidence of knowledge building. Our purpose is to provide insight into the characteristics of collaborative knowledge building and how it can be facilitated. To frame this study, we consider the conditions under which face-to-face collaborative knowledge building occurs in PBL, the characteristics of the discourse, and how a teacher/facilitator can provide affordances for knowledge-building discourse.

CONDITIONS FOR COLLABORATIVE KNOWLEDGE BUILDING

Several conditions are needed to support knowledge building (Scardamalia, 2002). First, people must work on knowledge problems that arise from attempts to understand the world. Second, they must work with the goal of improving the coherence, quality, and utility of ideas. Third, participants must negotiate a fit between their own ideas and those of others and use the differences they find to catalyze knowledge advancement. Fourth, there must be collective responsibility for advancing the community's understanding, and all participants must contribute. Fifth, participants must take a critical stance as they use various information sources. Finally, there must be knowledge-building discourse, which is more than knowledge sharing. In this kind of discourse, participants engage in constructing, refining, and transforming knowledge. We provide several examples of studies that demonstrate some of the features of collaborative knowledge building in Table 1. We identified characteristics of these studies that suggested that participants were engaged in knowledge building. In these studies, students worked collaboratively, problematized content, took responsibility for collective knowledge advancements, and engaged in deep discussions centered on knowledge problems (Cornelius & Herrenkohl, 2004; Engle & Conant, 2002; Hogan, Nastasi, & Pressley, 1999).

In collaborative knowledge building, the group activity is structured so that responsibility for learning is shared, expertise is distributed, and building on each other's ideas is the norm (Palincsar & Herrenkohl, 2002). Getting students involved

TABLE 1
Examples of Research Studies Viewed in Terms of Knowledge Building Characteristics

Study	*Context*	*Knowledge Problem*	*KB Appropriate Goal*	*Negotiating Toward Advancement*	*Collective Responsibility*	*Critical Stance*	*KB Discourse*
Engle & Conant (2002)	Fifth grade Facilitating Communities of Learners Classroom	Controversy over whether killer whales are whales or dolphins	Dealing with discrepant resources	Students used information resources to marshal evidence and develop counterarguments	All students made intellectual contributions and were accountable for building on each others' idea, presenting research, and developing group expertise	Students and teachers problematized content and information resources. Developed standards of credibility for resources	Developed arguments that became more elaborate and coherent over time
Hogan, Nastasi, & Pressley (1999)	Eighth grade students constructing and testing mental models	Building a theory about nature of matter	Effective groups worked to improve weak or incomplete ideas	Conceptual contributions used to deepen and refine ideas	Group members take responsibility for constructing explanation	Not addressed	Questioning and metacognitive statements initiate sustained knowledge construction as students acknowledge, built on and refine ideas
Cornelius & Herrenkohl (2002)	Fifth and sixth grade science classrooms learning to think like a scientist	Understanding sinking and floating	Deepening of evidence for/ against claims, students take on responsibility for monitoring	Argumentation supported by various cultural tools	Students increasingly participated over time (but this did not happen initially, required support of participant structures)	Rights and responsibilities entailed in being an audience for scientific claims (i.e., specific audience roles)	Persuasive discourse with interchange of largely student-generated questions, warrants/ claims, and other kinds of facilitating moves

in knowledge building engages them in working with meaningful problems, making constructive and critical use of authoritative sources, and having goals that emerge as knowledge building proceeds (Bereiter & Scardamalia, 2003). Progressive discussion is central to collaborative knowledge building as students create conceptual artifacts—in the case of PBL, these are the causal explanations of a patient problem. Knowledge building occurs when all participants are actively engaged and take responsibility for their own and other's learning (Rogoff, Matusov, & White, 1996).

To create conditions for knowledge building, participant structures are needed that engage students with knowledge problems and support moving classrooms beyond IRE discourse (Herrenkohl & Guerra, 1998). The usual mode of classroom discourse is the IRE pattern (Cazden, 1986) in which the teacher *initiates* a question, generally aimed at getting a student to display their knowledge, the student *responds*, and the teacher *evaluates* that response, thus, in this type of participant structure, students are not necessarily active agents in their learning nor are they engaging with knowledge problems. This type of structure encourages reproduction and display of knowledge rather than the progressive transformation and improvement of knowledge. Because knowledge building is a collective accomplishment, transformative discourse is critical. Special participant structures and cultural tools help support this kind of engagement in sustained discourse. A prominent feature in these participant structures is that students and teachers share responsibility for moving the discourse forward. These studies raise questions of how these participant structures support collaborative knowledge building and whether there are any characteristics that generalize across different participant structures.

PARTICIPANT STRUCTURES TO SUPPORT KNOWLEDGE BUILDING

To support collaborative knowledge building, teachers in inquiry classrooms often create carefully considered participant structures that "describes the distribution of the functional aspects of activity, including agency, authority, accountability, leading and following, initiating, attending, accepting, questioning or challenging and so on" (Greeno, 2006, p. 83). Different participant structures vary in how individuals are situated in terms of agency and authority; for example, who is expected to initiate questions or proposals for action. Participant structures that provide more symmetric student–teacher interactions encourage students to take on agency and enhance pedagogical efficacy (Tabak & Baumgartner, 2004). As classrooms are being increasingly organized around small group work, it becomes critical to understand the teacher's role in creating participation structures that have affordances for knowledge building (Polman, 2004). These new kinds of participant structures are needed to overcome the barriers of traditional classrooms in which the teacher does most of the talking (Cornelius & Herrenkohl, 2004).

The participant structure in Facilitating Communities of Learners (Engle & Conant, 2002) encourages students to take responsibility for their learning as they engage in research–share–perform cycles that emphasize students' active engagement in discursive activities. Similarly, Cornelius and Herrenkohl (2004) demonstrated that various tools, such as visual representations, encouraged discussion around scientific ideas and theories. Teachers helped facilitate collaborative knowledge building through questioning and prompts that built on students' ideas. Students became increasingly likely to take ownership for ideas and engage in persuasive discourse.

Studies of participant structures are helpful for deriving a big picture of particular features of knowledge building. They provide a great deal of detail on how students work on knowledge problems, the way they work toward knowledge-building goals, and to some degree, how they take on collective responsibility, and adopt a critical stance. However, such studies lack detail on the specific kinds of discourse moves that both teachers and students use as they engage in knowledge building discourse.

DISCOURSE MOVES ASSOCIATED WITH COLLABORATIVE KNOWLEDGE BUILDING

Three kinds of discourse moves are especially important in knowledge building. The first is questioning. Questions have specific purposes that can open up or constrain a dialogue as well as guide its direction (Burbules, 1993). Another type of move is a statement—this may be a simple assertion or development of a new view, reformulation, or elaboration of an idea. The third type of discourse move refers to regulatory statements that are directed at collaboration and learning processes. Together these moves enable knowledge-building discourse. This discourse requires participant structures in which students are active participants in identifying knowledge problems and collectively improving their ideas. It makes the student's thinking visible and open for discussion. The role of the teacher is to model their thinking processes and help students appropriate the social and epistemic rules for productive discourse (Collins, Brown, & Newman, 1989; Duschl & Osborne, 2002).

Hogan et al. (1999) studied the social and cognitive processes involved in construction of shared understanding during an eighth grade science inquiry unit while constructing a conceptual artifact (summarized in the second row of Table 1). In comparison to ineffective groups, effective groups often questioned each other, had few digressions, and spent more time engaged in knowledge construction.

Successful groups had many agreements and neutral reactions to other students' ideas whereas less successful groups were more likely to have disagreements. Questions or metacognitive statements generally initiated sustained episodes of knowledge construction. As in Engle and Conant's study, successful groups displayed an intellectual tenacity through a discursive give and take, in which participants acknowledged, built on, and elaborated on each other's ideas. These results suggest that certain kinds of moves are associated with knowledge building discourse but they are less clear about how opportunities for these moves are provided.

PROVIDING OPPORTUNITIES FOR KNOWLEDGE BUILDING THROUGH QUESTIONING

The literature on participant structures presents the larger context that describes the shared agency and overall activity structure and context but says little about the details of how responsibility for the discourse is shared and the kinds of discourse moves invoked. The studies do, however, suggest that questioning is an important aspect of collaborative knowledge building.

There are several cognitive and social functions of questions in discourse (Dillon, 1982; Graesser & Person, 1994). Questions can help with goal setting, guiding cognitive processing, activating prior knowledge, focusing attention, promoting cognitive monitoring, and promoting displays of knowledge (Burbules, 1993). One might ask information-seeking questions in response to a knowledge deficit. Questions can also be used to check whether participants have a shared understanding, which may be important in creating norms for collective responsibility. Participants may use questions to coordinate interactions thus allowing effective collaboration. Task-oriented and monitoring questions can help maintain effective group discourse, support metacognitive processes, and keep the group focused on the task at hand. They can help expose students' thinking and make it available for discussion of discrepancies that emerge and subsequent negotiation of understanding (King, 1999). Different types of questions can afford different kinds of reasoning, independent of the mechanisms that generated them. Questions that require deep reasoning and explanations are associated with improved learning outcomes (Graesser & Person, 1994; King, 1999; Webb & Farivar, 1999).

In participant structures that we have described, the students assumed a good deal of agency for knowledge building, but the teachers also had an important role. In Engle and Conant (2002), the teacher played a key role by promoting problematizing as she encouraged student questions, proposals, challenges, and other intellectual contributions. She helped students take on different roles by positioning herself as a learner and the students as teachers because of the expertise they had developed through their research. Similarly, in Hogan et al. (1999), the teacher's contributions were largely in the form of questions and never evaluative. In these ways, teachers provided opportunities for knowledge building.

Good teachers help provide learning opportunities for students and they often do so by asking questions rather than providing explanations (Chi, Siler, Jeong, Yamaguchi, & Hausman, 2001; Graesser & Person, 1994; Merrill, Reiser, Merrill, & Landes, 1995). Frequently, they use open-ended questions, hints, and prompts. These questions and prompts provide opportunities for student constructive activity (Chi et al., 2001; King, 1999). In many constructivist learning environments, such as PBL, students are responsible for knowledge building (Greeno, 1998). In these settings, students share responsibility for learning as the teacher helps provide affordances for knowledge building by facilitating student engagement with knowledge problems, encouraging negotiation among ideas, critical evaluation of resources and collective responsibility. Examples of such discourse occur in open-ended collaborative learning environments as the teacher plays a key role in structuring discourse by asking questions and helping guide students (Koschmann, Glenn, & Conlee, 2000; Meloth & Deering, 1999; Polman, 2000). We need to better understand how particular discourse moves can help create or impede opportunities for knowledge building.

Many of the participant structures described earlier are situated in inquiry classrooms. Inquiry teachers use a variety of discourse strategies that also promote constructive processing (Collins & Stevens, 1982). These strategies afford higher-order thinking and include having students learn what questions to ask. Such teachers tend to use questioning techniques that build on students' ideas to promote deep thinking (Van Zee & Minstrell, 1997) as in the three studies described in Table 1. In PBL, it is the students who assume much of the agency and authority for their own learning. Good questions can help students take on this responsibility (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, DeLeeuw, Chiu, & LaVancher, 1994; Graesser & Person, 1994). The research reviewed suggests that questioning is an important discourse move that supports collaborative knowledge building.

Although this literature on questioning describes forms of questioning and the reasoning that it affords, it does not address the shared agency needed for participant structures that promote collaborative knowledge building, such as PBL. These studies do not address specifically how different kinds of discourse moves are intertwined with the specifics of improving a conceptual artifact. Examining PBL with a knowledge-building lens suggests the need to examine discourse at different grain sizes to investigate how a small group works with knowledge problems to improve and transform their ideas. Before investigating how PBL supports collaborative knowledge building, we provide a further description of the PBL approach.

PROBLEM-BASED LEARNING

PBL is an active learning method based on the use of complex, ill-structured problems as a stimulus for collaborative learning (Barrows, 2000). Such problems may not have a single correct answer but require learners to consider and negotiate between alternatives and to provide a reasoned argument to support the solution they generate. The solution is a conceptual artifact in that it involves constructing an explanation. Students using PBL have opportunities to develop skills in reasoning and self-directed learning as well as to build a solid knowledge base. These opportunities require students to become responsible for their own learning and take collective responsibility for their group's progress as is characteristic of knowledge building. Empirical studies of PBL have demonstrated that medical students from PBL curricula are better able to apply their knowledge to problem solving and demonstrate more effective self-directed learning strategies than students in traditional curricula (Hmelo, 1998; Hmelo & Lin, 2000; Schmidt et al., 1996).

PBL is characteristically carried out in small groups of learners with a facilitator and takes advantage of the social aspect of learning through discussion, problem solving, and study with peers. The PBL teacher is a facilitator of student learning, whose interventions diminish as students progressively take on responsibility for their own learning. The facilitator helps monitor group discussions, guides students in the learning process, pushes them to think deeply, and models the kinds of questions that students need to be asking themselves (Collins, Brown, & Newman, 1989; Hmelo-Silver & Barrows, 2006). Learning occurs as students collaboratively engage in constructing and reformulating explanations for the problem. Students demonstrate increasing responsibility for their learning as they rely on information from other members of their group, ask questions, and construct explanations that support collaborative knowledge building. As noted earlier, PBL provides a participant structure that affords the six characteristics that Scardamalia (2002) has defined as knowledge building.

There have been few detailed studies of the cognitive and social processes in PBL tutorials. One set of examples comes from a special issue of *Discourse Processes,* in which several researchers analyzed the same six minutes of a videotaped PBL group meeting (Koschmann, 1999). Koschmann, Glenn, and Conlee (1999) identified several moves that the facilitator made in scaffolding the group's elucidation of their theory for the cause of a patient's medical problem. One move they identified was having the facilitator reformulate what students said in a way that helped them move forward in the discourse, similar to what O'Connor and Michaels (1992) termed "revoicing." In a cognitive analysis, Frederiksen (1999) concluded that the facilitator's actions ensured that the group's reasoning was organized and reflected a coherent approach to diagnostic inquiry as the group built a collective model of the patient's illness that reflected the reasoning that occurred. Palincsar's (1999) sociocultural analysis indicated that the facilitator had an important role in creating a culture in which the participants validated each other's ideas, established norms, and worked to achieve consensus. The facilitator played a pivotal role through contributions at key points that served to advance the problem-based discourse and scaffold learning. Each of these analyses look at a particular aspect of the PBL group meeting as they identified particular discourse moves, cognitive characteristics, and facilitation but like the studies of participants structures and discourse moves, they do not integrate the different levels of analysis needed to understand collaborative knowledge building. These analyses make important contributions to our understanding of conditions for productive discourse but they are based on a very brief slice of a single PBL meeting. It is difficult to derive pedagogical implications from such analyses. To examine knowledge building requires looking at a larger time scale, at least the course of a full problem and understanding the larger context in which knowledge building occurs.

Elsewhere, Hmelo-Silver and Barrows (2006) analyzed some of the data presented in this study to identify the goals and strategies of a facilitator. They found that the facilitator's goals for students included: (a) explaining disease processes responsible for a patient's symptoms and signs, and describing possible interventions, (b) employing an effective reasoning process, (c) being aware of their knowledge limitations, (d) meeting their knowledge needs through self-directed learning and social knowledge construction, and (e) evaluating their learning and performance. To meet these goals, he had a repertoire of strategies, which were flexibly applied based on what emerged in the group discourse. These goals and strategies seem quite compatible with a knowledge-building orientation but the analysis focused largely on the facilitator's goals and did not examine the tutorial with a knowledge-building lens.

In this study, we examine two PBL group meetings that occurred over five hours divided into two sessions as we investigate how a PBL group engaged in collaborative knowledge building. The group worked on the problem of a patient with pernicious anemia. The first meeting occurred before self-directed study as students used their initial understanding to engage in problem-solving discourse and to identify what they needed to learn; the second followed their self-directed study, as the group applied their new learning to the problem and reflected on their performance and prior understanding. We examine the facilitator's scaffolding of learning through questioning and the discourse features involved in the students' collaborative knowledge building. The major research questions that we address in this study include:

- How is knowledge-building discourse accomplished, and what are the characteristics of the interactions?
- How does the facilitator provide affordances for knowledge-building discourse?

- What characterizes the interaction within the group: between the facilitator and the students and among the students?

These questions are addressed through examination of knowledge-building episodes and fine-grained coding of discourse features. We develop multiple methodologies for analyzing the discourse that allows us to characterize knowledge building at fine, intermediate, and large grain sizes. We focus on characterizing the discourse as well as identifying discourse moves that the facilitator used to provide affordances for knowledge building and that are indicative of students' engagement in collaborative knowledge building.

METHOD

Data Sources

The participants in this study were five second-year medical students who were experienced in this PBL model, and a master facilitator, Howard Barrows (the second author). Barrows is a physician with a specialty in neurology, a medical educator, and an experienced PBL facilitator. Students worked as a group on a medical problem over 5 hours in 2 sessions. These students all knew each other but had not previously worked together as a group. Both sessions were videotaped and transcribed verbatim. The written transcript was annotated to incorporate what was being written on the whiteboards. Only the video of these two sessions was analyzed.

Instruction

A PBL tutorial session begins by presenting a group, typically five to seven students, with a small amount of information (Barrows, 1988; Hmelo & Ferrari, 1997). This amount of information is typical for an ill-structured problem in which not all the information is available at the start of the problem. Students obtain further information from a problem-based learning module (PBLM) (Distlehorst & Barrows, 1982). PBLMs are real patient cases in a book format that affords open inquiry. Students can ask many questions of the "patient" and receive the patient's response. They can request physical examination and laboratory tests in any sequence and learn the results as in the real clinical situation. The particular case used here was Ann George, a fictional name for a real patient case. She is a 72-year-old woman who presents to the clinic with a 4–5-week history of "numbness" in the bottom of her feet. Her feet feel funny as if there is "dried up skin." With appropriate inquiry and physical examination students can discover the following additional pertinent facts:

- The numbness has progressed up her legs to her hips in the last few weeks. Over the last few weeks she has noticed tingling in her fingertips.
- She has noticed some unsteadiness on walking, worse when she walks in the dark.
- No bowel or bladder complaints.
- Past history, family and social history are essentially unremarkable except for an episode of "shingles" last summer.
- She has slight spasticity in her legs to passive movement but normal strength. She was unable to tandem walk and had a tendency to lean toward either side. Slight dysmetria on finger to nose test bilaterally. Vibration sensation was markedly diminished at toes and ankles as well as fingertips. Position sense was significantly diminished in toes and fingers. The rest of the neurological assessment was unremarkable.

After the students completed the problem, they learned that the neurologist who saw the actual patient at the time of this presentation felt that she had evidence of involvement of the posterior columns and cortico-spinal tracts bilaterally and that most likely she had subacute combined degeneration of the spinal cord. The picture was so consistent with vitamin B12 deficiency caused by pernicious anemia that he ordered blood tests to check vitamin. B12 levels and a blood count. If these were normal then cervical spine disease (arthritis, tumor) and peripheral neuropathy would need to be considered. She had a markedly depressed B12 level and markedly elevated MCV (megaloblastic anemia). B12 injections were initiated.

The patient's problem, pernicious anemia, is an autoimmune disease in which a lack of intrinsic factor in the stomach prevents vitamin B12 from being absorbed from the gut. The lack of B12 causes both slow degeneration of nerve fiber bundles (columns) in the spinal cord and a megaloblastic (large red cells) anemia. Pernicious anemia is not common, and it is subtle as its onset may not be apparent for a long time. If not treated early, the damage to the nervous system can become irreversible. This patient eventually recovered following B12 injections.

From the outset, students are challenged to generate hypotheses that guide their inquiry through the PBLM. At several points, students pause to reflect on the hypotheses they have collected so far, generate questions about the data, and generate ideas about solutions. Students identify concepts they need to learn more about to solve the problem (i.e., learning issues). After considering the case with their existing knowledge, students divide up and independently research the learning issues they identified. They then regroup to share what they learned, and reconsider their hypotheses and decisions in light of what they have learned. When completing the task, they reflect on the problem to consider the lessons they learned, as well as how they each performed in their self-directed learning and collaborative problem solving.

While working, students use whiteboards to help scaffold their problem solving. The whiteboard is divided into four columns, labeled *facts, ideas, learning issues,* and *action plan,* to help them record where they have been and where they are going. The whiteboard serves as a focus for group deliberations and as an ongoing worksheet. The *Ideas* column serves to keep track of their evolving hypotheses. The *Facts* column holds information that the students obtained from their inquiry into the problem. The students place their identified learning needs into the *Learning Issues* column. They use the *Action Plan* column to keep track of plans for resolving the problem or obtaining additional information. Students have many opportunities for constructive thinking through their discourse and the artifacts that they use to represent their thinking. Many groups create an additional representation as they map out their causal hypotheses to account for the patients' signs and symptoms and their approach to treatment.

Analysis

We took multiple approaches to analyzing these data (Chi, 1997; Erickson, 2006). The transcript was initially examined at two grain sizes during the two tutorial sessions. At a large grain, we looked for examples of knowledge-building discourse as they emerged from the data. This analysis involved looking for indications that students saw something in need of explaining, made efforts after coherence, and made collective efforts to advance the group's understanding. In particular, we focused on progressive deepening of the group's understanding of the patient's diagnosis of pernicious anemia, a type of vitamin B12 deficiency that accounts for the patient's signs and symptoms. This analysis addresses the research question about how knowledge building is accomplished.

To characterize facilitator and student contributions to the discourse at a fine grain, the transcript was coded for the types of questions and statements made. This coding strategy addresses questions about the characteristics of interactions within the group and some of the ways that the facilitator provides affordances for knowledge building. Questioning by the facilitator is important because it creates affordances for constructive processing. Questioning by students indicates their uptake of questioning as a norm for engaging in knowledge-building discourse. The unit of analysis was generally the conversational turn. A new turn was considered to start when the speaker changed.[1] These were parsed into additional units when either the topic of conversation changed or when a different type of discourse move was observed. For example, if a student made a statement and generated a question in a single turn, this was parsed into two units.

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[1]Although, as one of the reviewers point out, this is not a completely unproblematic definition (Bloome & Clark, 2006), it is used consistently and proved adequate for these analyses.

All the questions were identified based on grammatical form or rising intonation. They were coded using Graesser and Person's (1994) taxonomy of question types as well as additional categories that captured monitoring, clarification, and group dynamics questioning (see Table 2). These categories captured the depth of reasoning that the questions elicited as well as the student and facilitator's monitoring of collective understanding and task-related progress. Although these coding schemes have been applied to whole class discussions and tutoring dialogues, they have not been applied to small group interactions such as PBL tutorials. Three categories of questions were coded. Short-answer questions required simple answers of five types: verification, disjunctive, concept completion, feature specification, and quantification. Long-answer questions required more elaborated relational responses of nine types: definitions, examples, comparisons, interpretations, causal antecedent, causal consequences, expectational, judgmental, and enablement. The first two types of long-answer questions can help lead to comprehension-oriented discourse (King, 1999) whereas the others are more likely to lead to knowledge building because they require inferences and deep reasoning. These patterns are associated with greater levels of learning as students clarify their thinking, deal with conceptual discrepancies, and continually reorganize and restructure their ideas. The task-oriented/meta category referred to group dynamics, monitoring, self-directed learning (SDL), and clarification-seeking questions.[2] Questions that did not fit into these categories were classified as uncodeable.

To examine how ideas were introduced into the group discourse and how group members built on each other's ideas, statements were coded as to whether they were new ideas, modifications of ideas, agreements, disagreements, or metacognitive statements as shown in Table 3. Statements were coded as metacognitive statements if they were geared toward monitoring collective or individual understanding (e.g., "I think this makes sense"), task-related progress (e.g., we need to write a new problem definition), and self-directed learning (e.g., "I think that should be a learning issue").

Each of these statements was also coded for complexity to identify the sophistication of the reasoning and degree of constructive processing (see Table 3). Statements were coded as simple if they were assertions without any justification or elaboration. Simple statements included verifications, concept completions, and quantities. Elaborated statements went beyond simple assertions by including definitions, examples, comparisons, judgments, and predictions. Causal statements described the processes that led to a particular state or resulted from a particular event. Causal statements are presumed to represent deeper processing than elaborated statements, which in turn represent deeper processing than simple assertions. Statements were also coded as to whether they were read from the case information, a repetition of a previous statement, or an uncodeable statement. If students

[2]Task-oriented/meta questions will be abbreviated simply as meta questions.

TABLE 2
Categories of Questions

Question Type	*Description*	*Example*
Short answer		
1. Verification	Yes/no responses to factual questions.	Are headaches associated with high blood pressure?
2. Disjunctive	Require a simple decision between two alternatives	Is it all the toes? Or just the great toe?
3. Concept completion	Filling in the blank or the details of a definition	What supplies the bottom of the feet? Where does that come from?
4. Feature specification	Determines qualitative attributes of an object or situation	Could we get a general appearance and vital signs?
5. Quantification	Determines quantitative attributes of an object or situation	How many lymphocytes does she have?
Long Answer		
6. Definition	Determine meaning of a concept	What do you guys know about pernicious anemia as a disease?
7. Example	Request for instance of a particular concept or event type	When have we seen this kind of patient before?
8. Comparison	Identify similarities and differences between two or more objects	Are there any more proximal lesions that could cause this? I mean I know it's bilateral.
9. Interpretation	A description of what can be inferred from a pattern of data	You guys want to tell me what you saw in the peripheral smear?
10. Causal antecedent	Asks for an explanation of what state or event causally led to the current state and why	What do you guys know about compression leading to numbness and tingling? How that happens?
11. Causal consequence	Asks for explanation of consequences of event/ state	What happens when it's, when the, when the neuron's demyelinated?
12. Enablement	Asks for an explanation of the object, agent, or processes allows some action to be performed	How does uhm involvement of veins produce numbness in the foot?
13. Expectational	Asks about expectations or predictions (including violation of expectation)	How much, how much better is her, are her neural signs expected to get?
14. Judgmental	Asks about value placed on an idea, advice, or plan	Should we put her to that trouble, do you feel, on the basis of what your thinking is?

(Continued on next page)

TABLE 2
Continued.

Question Type	*Description*	*Example*
Task oriented and meta		
15. Group dynamics	Lead to discussions of consensus or negotiation of how group should proceed	So Megan, do you know what they are talking about?
16. Monitoring	Help check on progress, requests for planning	Um, so what did you want to do next?
17. Self-directed learning	Relate to defining learning issues, who found what information	So might that be a learning issue we can, we can take a look at?
18. Need clarification	The speaker does not understand something and needs further explanation or confirmation of previous statement	Are you, are you, Jonathan are you talking about micro vascular damage that then, which then causes the neuropathy?
19. Request/Directive	Request for action related to PBL process	Why don't you give, why don't you give Jonathan a chance to get the board up.

were building deep conceptual models, then the discourse should show evidence of sophisticated, elaborated, and causal statements.

To check coding reliability, two independent raters coded 20% of the discourse; interrater agreement was 90% for question coding and 87.5% for statements. Frequency distributions of the codes by speaker (facilitator or student) were compiled. In addition, we examined how the discourse differed across the two sessions.

Based on the results of the first two analyses, an additional analysis was conducted at an intermediate grain size to further examine how the discourse was moving forward and being maintained. This analysis further addresses the facilitator and student roles in the PBL tutorial. For this analysis, the transcript was parsed into episodes. Parsing was done when either the subject of discussion changed or the function changed (similar to Hogan et al., 1999). An example of the former would be change from talking about multiple sclerosis as a hypothesis to pernicious anemia. An example of the latter would be a change from generating hypotheses to organizing their current ideas. For each episode, we tracked who initiated the episode, the type of initiating discourse move, the length of the episode, and the longest run of student talk uninterrupted by the facilitator. The episode length suggests engagement with a particular topic or task and the length of the student runs indicates the extent to which students were driving the discussion. Notes were also made regarding the content and/or context for the episodes.

TABLE 3
Categories of Statements

Statement Type	*Definition*	*Example*
Collaboration		
1. New idea	Mentioned idea not previously introduced	Uh, it's a deficient, deficiency of cobalamin
2. Modification	Changing an idea previously mentioned—may include elaboration, clarification, revision	Vitamin B12, cobalamine or
3. Agreement	Indication of shared opinion or understanding	Oh. You're right.
4. Disagreement	Indication of difference of opinion or understanding	But their ileum is gone and they can't absorb the B12. That's different than pernicious anemia.
5. Meta	Indication of monitoring individual or group understanding, progress, self-directed learning	We all just did a, we kind of talked about something that wasn't right. And you clarified it. That the pernicious anemia refers specifically to vit, intrinsic factor.
6. Other	Statements that do not fit into categories 1–5 or were unintelligible	Hmmm. That's [unintelligible]
Complexity (for categories 1–4)		
1. Simple	Claims or assertions without any elaboration or justification	Like pernicious anemia is a big one.
2. Elaborated	Statements that include definitions, examples, comparisons, judgments, and predictions without causal warrants	Technically pernicious, pernicious anemia is technically just the loss, the lack of intrinsic factor.
3. Causal elaborated	Includes explanation of how an event or process occurs, how current state arose, or consequence of a process or event	Vitamin B12 and folate both lead to megaloblastic situation.

RESULTS

From Hypotheses and Learning Issues to Coherent Explanation

In the discourse examples in this article, we use instances of students talking about how a B12 deficiency led to pernicious anemia and how that caused the patient's problem of numbness of the feet and a clumsy way of walking. These examples allow us to trace how students were thinking about what became the major causal hypothesis, pernicious anemia, a vitamin B12 deficiency that occurs because of the absence of a factor needed to absorb the vitamin. This hypothesis was first introduced early in the first session during a period of rapid hypothesis generation:

Megan:[3]	. . . in a patient who presents with any of these signs. There's thyroid problem possibly, vitamin deficiency we talked about, vitamin B1 or vitamin cobalamin, vitamin B12. Um, there's also like the alcohol toxin problem. Um . . . diabetes. [Jonathan writes on board]
Donna:	You might want to put up specific under malnutrition uh, the B vitamins.
Facilitator:	So why'd you say hypothyroidism? You guys are so fast I can't keep up with you. Why'd?

In this part of the tutorial, the students were proposing many hypotheses based on a limited amount of patient data. These proposals were partly to help them focus their subsequent inquiry. The facilitator encouraged students to back up and make their thinking visible as he went back to the thyroid problem that Megan mentioned. All the hypotheses went onto the whiteboard as the facilitator ensured that most of them were discussed further. Often the whiteboard was used as a tool to promote this discussion as the students were evaluating their hypotheses later in the first session:

Facilitator:	Megan does that malnutrition vitamin B cover the, the things you were talking about just a minute ago? You were concerned about there's a number of different vitamins that may be involved.
Megan:	I hmmm.
Facilitator:	Can we just leave the, that hypothesis up?
Megan:	Oh yes. I think that's fine.
Donna:	Like pernicious anemia is a big one.
Megan:	Right. That must be the vitamin, the B.

Here Donna substituted pernicious anemia for vitamin B12 deficiency, and the facilitator used this change in terminology as an opportunity to help the group realize what they did and did not understand about this condition.

Facilitator:	What, what's pernicious anemia?
Donna:	Uh, it's a deficient, deficiency of cobalamin.
Megan:	Vitamin B12, cobalamin or . . .
Jim:	Or folate.
Megan:	Or folate.

[3]All names are pseudonyms.

Donna: Yeah, but it's not, that's not pernicious anemia. That's a, also another macrocytic anemia.
Megan: Pernicious anemia is specifically.
Jim: Oh. You're right. That's right.
Donna: And um, you get anemia and you can also get eh, um, peripheral . . .
Megan: Neuropathies.
Donna: . . . neuropathies.
Facilitator: . . . down there too?
Cheryl: Technically pernicious, pernicious anemia is technically just the loss, the lack of intrinsic factor.

Donna: The loss of intrinsic factor. So you don't absorb . . .
Megan: Right. That's a good distinction. You see, we just . . .
Cheryl: As opposed to like somebody who had part of their intestine removed and can't absorb . . .
Cheryl: We kind of lump it all together, right?
Donna: Yeah.
Megan: We all just did a, we kind of talked about something that wasn't right. And you clarified it. That the pernicious anemia refers specifically to vit, intrinsic factor.
Cheryl: Right.
Megan: But it's tied in with vitamin B12.
Cheryl: Right.
Megan: Vitamin B12 and folate both lead to megaloblastic situation.
Cheryl: Right. Macrocytic.
Jonathan and Jim: Microcytic anemia.
Megan: . . . microcytic and macrocytic anemia. Right?
Facilitator: So should we have pernicious anemia up as a hypothesis?

In this last excerpt, the students had a discussion in which they displayed their knowledge about pernicious anemia. It was clearly limited to a few facts that distinguish it from other kinds of anemia and causes of B12 deficiency—that it is caused by the inability to absorb it from an intact gastrointestinal tract, and that it is an anemia (red blood cell deficiency) characterized by large (macrocytic) cells that are not just large but immature as well (megaloblastic). There was no discussion of mechanism for either the blood cell abnormalities or the numbness and tingling with which the patient presented. The facilitator reminded Jonathan, the scribe, to get this on the hypothesis list by calling attention to it with the question that ended this episode. This excerpt shows that there was an early goal of making students' thinking visible as they documented their ideas on the whiteboard and opened them for discussion and improvement.

TABLE 4
Hypotheses and Learning Issues at Conclusion of Session One

Ideas	*Learning Issues*
Diabetic neuropathy	Guidelines for hypertension
Multiple sclerosis ↓	Diabetic neuropathy
~~Alcoholic neuropathy~~	Multiple Sclerosis
~~Malnutrition~~	Peripheral neuritis
Afferent Neuropathy	Innervation of foot and Blood supply
Peripheral neuritis ↓	Pathophysiology of numbness
~~Guillain Barré syndrome~~	Guillain Barré
Spinal cord lesion ↓	Paresthesia
Spinal cord Tumor	Paralysis
Compression fracture ↓	Afferent Tracts
Herniated Disc ↓	Arcus Senilus
~~Hypothyroidism~~	Broad based gait Romberg
Toxicity	Cerebellar function
Arsenic	Muscle tone resistance
Lead	Olivopontocerebellar atrophy
~~Anemia~~	CSF studies
~~Pernicious~~	
~~Scleroderma~~	
Electrolyte problem	
~~Psychiatric disorder~~	
CNS tumor	
CNS Infection	

Note. The ideas column indicates the students' hypotheses and reflects decisions about removing and downgrading hypotheses in importance.

Table 4 shows a reconstruction of the hypotheses and learning issues that the group was considering at the end of the first session. There were 20 hypotheses written on the whiteboard during the first session and 17 learning issues. There was a rather broad range of issues that the students were considering. They did not have a clear leading hypothesis at the end of the first session. The facilitator pushed each student to commit to a hypothesis, rendering explicit their leading ideas and knowledge limitations regarding their hypotheses as he said "What? When it's all said and done. What does, what does, what is, what is uh Ann George going to turn out to have? In your guess, I mean, eh, want to take a change of heart when you find more things. But at this moment, with the data you have, what do you say?" The students then identified their leading hypotheses, none of which included pernicious anemia. As the students ranked their hypotheses near the end of the session, the group decided that pernicious anemia was not a likely candidate, and they crossed it off the list as they mapped some common symptoms of anemia to the patient's symptoms such as dyspnea (shortness of breath) and her color.

Megan:	Right. That's maybe, it might be ruling out of, outside of excluding. We'll have to look into that more. Anemia?
Jonathan:	She doesn't seem anemic. [crosses out "anemia"]
Megan:	No. She has no dyspnea. No pale conjunctiva.

Their list of learning issues (Table 4) did not include pernicious anemia although many other hypotheses were included for further research, as were some of the signs and symptoms for which they did not understand the significance (e.g., paresthesia, broad-based gait) and some anatomy and physiology that they felt they needed to better understand. They identified issues connected to the central nervous system, its disorders, and relevant signs and symptoms. The students divided up the learning issues as the facilitator helped monitor the distribution of learning issues and encouraged the students to all make sure that they each had a "big" issue. There was no evidence of a coherent understanding but the group had numerous ideas to refine and transform.

Pernicious Anemia Returns.

When the students returned for the second session, following their self-directed learning, they brought pernicious anemia back for consideration. The first clue to this reconsideration occurred as Jonathan summarized the patient case and concluded by saying "Right now . . . our differential list includes particularly a vitamin B12 deficiency. We've discussed um, also neurosyphilis or some other uh CNS injuries." The students' reports on their self directed learning strategies indicated that several of the students came across this condition as an important possible hypothesis in need of explaining as this next excerpt shows:

> And another important um, hypothesis that's come is a vitamin B12 deficiency, which we've crossed out. Hah, because we didn't think she had any malnutrition. However, we found out that um, in the elderly there is a much, much higher prevalence of Vitamin B12 deficiency. And what's extremely interesting is that those patients don't always present with megaloblastic anemia, which you'd think would be the pathognomic sign for vitamin B12 or folate deficiency.

Here Megan was noting some general features of the disease, and in particular, a feature that she expected to be part of the patient presentation as the "pathognomic sign." But then Megan went on to make a mapping between the signs and symptoms normally seen in this disease and those that the patient actually exhibited:

> In fact, many elderly people present first with a neurological deficits before they present with any other problems. And it just so happens that our patient symptoms fit almost ex, ex, exactly to the neurological sym, uh symptoms of a B12 deficiency. She's got weakness and tingling, especially the tingling in the peripheral extremities.

> Um, she has decrease in vibration position sense. That's also um, indicative of this sort of problem. Many times they'll present with um, cognitive deficits or possibly even mild psychosis. She doesn't have those, but it's something that we need to treat immediately if, if there is a, a decreased level of cobalamin because um, it can progress to paralysis. And once it does you have no um, there's no way to reverse those neurological changes. So I think we need to do, not only a CBC, but even if the CBC comes back with normal red cell indices, we need to do um, cobalamin level actually. Check that . . .

After Megan accomplished this mapping and made some suggestions about how to test the pernicious anemia hypothesis, Donna jumped in to agree with what Megan said and then went on to elaborate the importance of considering this hypothesis:

Donna:	And also, I was just, happen to glance at it last night and um, 'cause I was just talking with my husband and, about the um, neurosyphilis and, and uh, the olivopontocerebellar atrophy being pretty serious and progressive and, and I was thinking that vitamin B12 wasn't so much if you treated it. But it, I was reading that it's in a lot of the neur, uh, neural deficits are irreversible.
Megan:	Uh hmm.
Donna:	So it is, you know. It does put in my mind it's a more of a serious.
Facilitator:	Now you people are saying B12 all the time and yet when you say we eliminated it, you're talking about pernicious anemia, right?

The facilitator jumped in and revoiced some of what Donna and Megan had said (O'Connor & Michaels, 1992). First, he made it clear that both students were discussing the same condition. Second, he recognized Donna's contribution to improving the group's collective understanding. The group began to move from mapping symptoms to mechanisms after the facilitator asked "So how are we on pernicious anemia? I want to finish up that list." This prompt led them into a discussion of *how* lack of intrinsic factor can cause a B12 deficiency.

Megan:	Well, she might not have pernicious anemia. I mean, it's possible. What we need to do is, is check.
Cheryl:	Wouldn't that be the more likely though?
Jonathan:	No.
Donna:	No. Well, not, not necessarily.
Cheryl:	Because she's in her seventies, the lack of intrinsic factor is more common.
Megan:	They, they often. Actually they often have atrophic gastritis, elderly people.
Cheryl:	That's true.

Megan: And eh, so those people even if they have intrinsic factor, cannot, still cannot absorb the vita, vitamin B12.

Donna: Yeah. One thing I read was achlorhydria. If they get um, that decreases the amount of cobal, cobalamin that can be absorbed because it binds to um, an R factor or something that. . .

Megan: R, you cannot cleave the R binder from the transpondent.

Donna: . . . that, that competes with intrinsic factor so that it's not. Even if you have intrinsic factor, it's not affected because it can't bind with cobalamin.

Jim: Well, that, that's exactly it. Like 90 or 10% of the, of elderly that have a vita, vitamin B problem is due to pernicious anemia. The other 90% . . . is due to the fact that, that when you . . . ingest vitamin B12 it's complexed with a protein, an R protein. And they lack the ability to break that protein apart to have the vitamin B site of cobalamin free. So then it can bind to the intrinsic factor. So if they, it's not binding . . . if it's not breaking off, you may, you may have tons of intrinsic factor, but since it can't get a hold of it, it's like not gonna do.

The group worked together to improve their collective knowledge as most of the group members contributed to an explanation of this piece of the puzzle. They refined their ideas into in an integrated causal explanation of why B-12 cannot be absorbed, as Jim summarized. Once there were no new ideas or elaborations being offered, the facilitator provided a boundary to this episode of hypothesis evaluation by using the tools of PBL as he said to the scribe "So you, Jonathan, need to straighten the board up a little bit." Straightening up the board suggested to the students that they needed to continue going down their lists of hypotheses on the board, removing the ones that no longer seemed viable.

The Drawing Episode

As seen in the excerpts presented previously, several students had found pernicious anemia as part of the differential diagnosis while they were researching other learning issues and Megan brought it back front and center. By the end of the second session, the students constructed a remarkably coherent understanding after the facilitator asked them to integrate their understanding in a diagram. "Um, probably the best way to, to pull this all together I suppose is to uh, uh tell me what you think is involved in her nervous system. Can you uh, can you draw a diagram of where you think the problem is?" This prompt led to a rich 29-minute discussion in which group members engaged in collaborative knowledge building as they worked to fit their ideas together and consolidate their understanding. This episode had roughly three phases: a brief phase in which they planned the

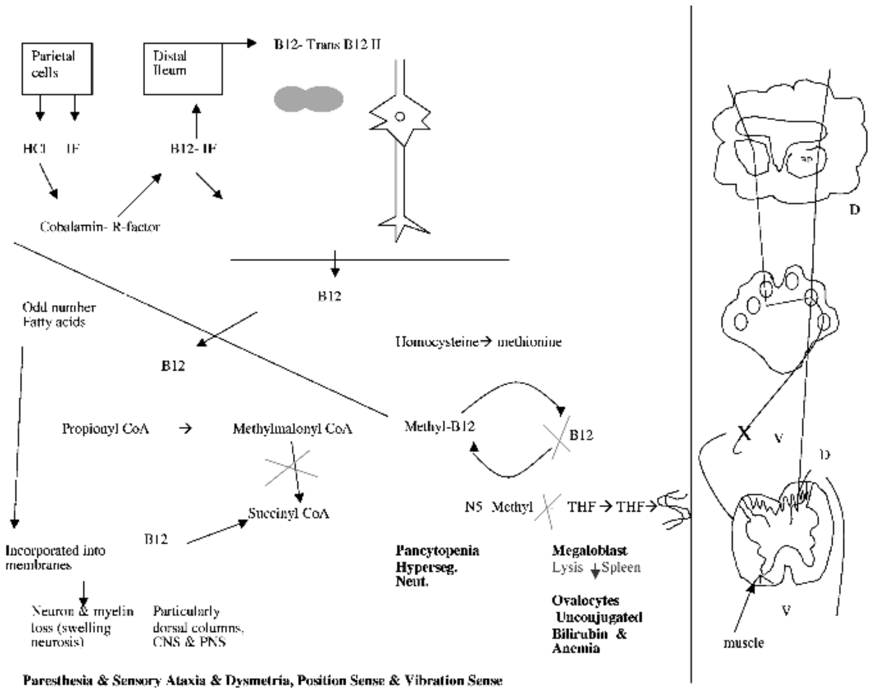

FIGURE 1 Student-generated flow chart.

drawing, the bulk of the drawing phase with an important segment in which the students made the connections between the signs and symptoms and different levels of functioning, and finally, a wrap-up that was characterized by references to the drawing and tying up loose ends. The groups' final drawing is represented in Figure 1.

Getting started. After the facilitator proposed the drawing, one of the students suggested perhaps they might incorporate it into a flow chart with two of the other students chiming their agreement. They then got started as the facilitator asked the students "Where are you starting . . . with the patient or the biochemistry?"

Jim:	We can start with intrinsic factor and...
Megan:	Yeah we can start with saying...
Jonathan:	. . . then getting more into the symptoms.
Megan:	. . . How do you get vita, vitamin B12 into the body? What is it used for?

Donna:	So with, yeah.
Megan:	And without it, what happens?
Donna:	So with the actual patient, she lacks intrinsic factor, which is her primary problem.
Jonathan:	Okay.
Megan:	Hah. So parietal cells in the . . .
Donna:	Oxyntic gland, or fundus.

In this segment, the students started with familiar concepts. The talk came rapidly, and all the students were involved in constructing the drawing and integrating their ideas. Although the students referred to the patient's primary problem, they only referred to it in general terms. Here, they were largely going back and forth between a discussion of anatomy and biochemistry. Jonathan, the scribe, had no trouble following the conversation. Megan framed their task as dealing with the role of B12 and intrinsic factor as the common framework to explain the case, and the other students quickly agreed. Contrast this agreement with the disparate hypotheses that reflected students' thinking at the end of the first day, shown in their whiteboard portrayed in Table 4. The students had strong common understanding of these concepts. They were working with ideas that had already been discussed, and there was strong consensus as they were doing this initial representational work. In general, the talk was not very elaborated as the students completed each other's ideas and provided simple clarifying responses. In this phase of the drawing, the groups' activity really focused on what they had learned about anatomy and biochemistry. They were not integrating it with the patients' signs and symptoms.

Mapping between causes and effects. After a fairly detailed discussion of the biochemistry, Jonathan and Jim had a brief discussion about representational conventions.

Jim:	One of, one of the last things about that besides the, which you're going to write the, you should write that up about the megaloblastic cells, just as another arrow.
Jonathan:	Yeah we could have like symptoms here.
Cheryl:	Uh hmm. Yes.
Donna:	Yeah. Yeah.
Jonathan:	I'll draw the symptoms in black.

This last statement began the next phase as the students started connecting their hypotheses about causal mechanisms (i.e., anatomy and physiology, biochemistry) to the evidence (i.e., the signs and symptoms). Making this connection was important because the discussion of how to represent processes and signs and symptoms moved the students' thinking forward; thus the representation served as a tool in their collaborative knowledge construction and a focus for negotiation.

The student discourse was related to the drawing activity. As they switched between different levels of representation (e.g., from physiology to clinical signs) they participated in an episode of extended knowledge building. Near the junctures where student drawing activity switched from drawing representations of basic science processes to signs and symptoms or between levels of science, the students engaged in causal talk. In addition, the students were involved in a great deal of elaboration and monitoring as their drawing progressed. In the discussion preceding this next excerpt, the students had largely focused on basic science mechanisms without connecting their ideas to the patients' signs and symptoms. The facilitator jumped in and asked: "Okay. Now you're going to bring it into the nervous system?" The students responded to this by first improving and completing their biochemical explanation but then connecting it to the clinical signs (signified in bold in Figure 1 and examples that follow).

Jim:	We, you start with a odd number fatty, odd number of carbons for the fatty acids.
Megan:	Fatty acids.
Cheryl:	Right.
Megan:	And then you incorporate it a, a carbon dioxide that it's a carboxylation reaction for the propianol Co-A to the methylmalanil Co-A. So you convert it from an odd chain with three to a four chain and then you do, it's actually a mutase reaction for the methyl.
Jim:	Carbonyl.
Jonathan:	Carboxylase?
Megan:	Pardon.
Jonathan:	Is it carboxylase?
Megan:	Um, maybe it's, I don't know if malino Co-A carboxylase. It's propianol Co-A carboxylase is the name of it.
Jonathan:	Okay.
Megan:	But that's not as important as . . .
Donna:	You need a CO2.
Megan:	Yeah, and the next one actually is a, so you got it to a four chain with this, which is the methylmalinal Co-A. And then that, the um, the next step is actually just a mutase which rearranges the four carbon chain to succinyl CoA. Right.
Jonathan:	So basically, this is the part that knocks out.
Megan:	Yeah, that's the process.
Jonathan:	So these get incorporated into the . . .
Megan:	Membranes.
Jim:	In the handout that I gave you, the last sheet gives the um pathogenesis of this vitamin B12 deficiency.

Jonathan: So incorporated into the membranes and then you get . . . neuron loss, demyelination.
Jim: Specifically dorsal column. Yeah. Specifically dorsal column.
Megan: Right.
Jim: And it, it's called like the, the term, the category is a, is a metabolic demyelinization.
Megan: And you get neuronal also um, various things that happen. I believe you get neuronal cell swelling within the membrane and then you can get neuronal death. And that's when you get **the paralysis** and once it progresses to that stage, as we know, neurons will regenerate.

At this point, the students went through a causal explanation in which they clarified their ideas and integrated different levels of analysis, although they only just began to get to the clinical level; in fact, they brought their explanation to the level of a hypothetical symptom. The students engaged in causal elaborations just before they switched their drawing from anatomy and physiology to signs and symptoms. Previously, the students had not made explicit connections between what was going on at cellular, anatomic, and clinical levels; thus here they were integrating their understanding and improving their collective knowledge. The students got more specific and started to identify the location of the structural and functional abnormalities that accounted for the patients' symptoms in response to the facilitator's question "Okay now you want to, would you please summarize those structures that are involved in the nervous system. What, where is that happening? This swelling of the neurons and loss of myelin."

Jim: Dorsal column.
Megan: Dorsal column, specifically dorsal column.
Cheryl: Yeah.
Donna: Just.
Facilitator: Is that it? Just the dorsal columns?
Cheryl: That's the main place right? It doesn't happen in . . .
Jim: That's what causing her symptoms.
Jonathan: What are her symptoms?
Donna: And then, then Megan eventually do you get um . . .
Jim: **Paresis, paresthesia**.
Jonathan: **Paresthesia.**
Jim: Which is **numbness and tingling and hyperexcitability**.
Jonathan: Okay.
Cheryl: Um . . . and then the loss of . . . yeah
Jim: And then **gait**.
Cheryl: Then the loss of, yeah. The **proprioception and vibratory loss**.
Megan: Ataxia, sensory ataxia is what it's called for the gait abnormality.
Facilitator: You want to describe what sensory ataxia means?

Megan went on to define sensory ataxia, an inability to coordinate muscle movements due to sensory abnormalities, and Cheryl noticed that her symptoms were not a perfect match for that description. Here the students were getting closer to bringing the problem of demyelination to specific structures (the dorsal column) and then mapping it onto the signs and symptoms that the patient was actually exhibiting (in bold). Moreover, they were monitoring the fit between the symptoms that she was exhibiting and their theoretical descriptions. All the students were engaged in this collaborative sense-making activity that was getting them close to their goal of a coherent causal understanding. The drawing was an important tool in this discussion. It served as a concrete referent that students could point towards and negotiate as they were elaborating and monitoring their joint understanding.

Wrapping up. In the final phase of the drawing activity, the representation made salient aspects of the group's understanding that were lacking (and needed improvement) as they made frequent references to the drawing. Because the drawing that they constructed up to this point was the largely biochemical explanation, shown on the left side of Figure 1, they still needed to make the connection to structural and functional abnormalities. There were gaps in the drawing activity as students negotiated what they needed to fill in. The facilitator began by asking the group about consensus for the locus of the neurological problems. The students made some connections between their hypotheses about the nervous system and the symptoms that the patient exhibited:

Facilitator:	So your summary then of the problem in the nervous system is the dorsal column? Is that what you're saying?
Megan:	Uh hmm.
Jonathan:	Yeah.
Facilitator:	Bilaterally. And that doesn't surprise you in a metabolic problem that it's bilateral?
Megan:	No.
Cheryl:	Uh uh.
Facilitator:	Yes, no? Anything else involved in the nervous system?
Jim:	Well, um. This is mentioning the same thing really, but to solve the upper motor neuron problem, which they say in vitamin B12 deficiency you get that **hypertonicity**, which we do have. So, again it's another, more support for this hypothesis about the motor neurons.

But then Donna noticed an inconsistency and Jim noticed that the group had not really focused on the dorsal tracts of the spinal cord, despite the fact that they were referring to it fairly extensively. At this point the group was into the final phase of the drawing episode. They were working together to understand the anatomy, drawing the diagram on the right side of Figure 1 and gesturing towards it during their conversation.

Donna:	So it also is involving something besides the dorsal columns.
Jim:	Do we want to talk about the tracts since we keep using the terms?
Megan:	Yeah.
Donna:	Sure.
Jonathan:	Couldn't take long.
Megan:	You're talking about dorsal columns in the, and the . . .
Jonathan:	I've drawn the spinal cord, basal medulla, and the brain. This is the thalamus is like . . .
Cheryl:	I was wondering what those were. (laughing)
Jonathan:	The thalamus is huge in this person, but. But uh, I'm not an artist. Um, this is of course dorsal, ventral . . . (points to diagrams; puts "D" to represent dorsal and "V" for ventral in each picture).

Jonathan then began to refer to the drawing on the right side of Figure 1 that he was sketching. Jim provided an invitation for the rest of the group to join him in explaining the representations. Throughout the entire next segment, the students were gesturing toward the representation.

Jim:	Go ahead we'll throw stuff in. Cheryl: We'll help.
Jim:	Okay. Well this is the dorsal um, dorsal columns . . .
Cheryl:	Uh hmm.
Megan:	Made up of?
Jonathan:	They um, they're divided somewhat. This is um, the gracilis, fasciculus gracilis, gracil graceful means slender so that's why it's a little slender piece here. And that's more the upper extremities. Or excuse me, lower extremities.
Megan:	Lower.
Cheryl:	Lower.
Jonathan:	The lower extremities. And then the . . .
Cheryl:	Cuneatus.
Jonathan:	Fasciculatis cuneatus is the upper extremities. It's, means cone.
Jim:	Wedge.
Cheryl:	Or wedge.
Megan:	Wedge.
Jonathan:	Wedge-shaped.
Donna:	That's a good way to remember it.
Jonathan:	And that's where **vibration, position sense, and light touch . . . travel.** And they travel ipsolateral.
Megan:	As well as **proprioception?** Did you say that?
Jonathan:	Yeah.
Megan:	Or uh **stereognosis** is what I meant to say.
Jonathan:	**Stereognosis** yeah.

The students worked together to construct this explanation and although they were largely drawing an anatomic diagram, they were still making connections to clinical medicine (i.e., the signs and symptoms) as they noted what was responsible for particular sensations that were disrupted in this patient. They also engaged in elaboration as they noted that the names of some of the structures have meanings that describe their physical appearance.

Jim:	Do you want to draw the pathways?
Jonathan:	I'm going to do that.
Jim:	And where it crosses over.
Donna:	Yeah, let's just.
Jonathan:	(draws arrows indicating pathways) Yeah, as it goes up, they come in, and then they travel up. And then they travel, there's um, in the basal medulla, you've got three nuclei here. Dorsally. There's one called the gracilis and the cuneatis, which is go all the nucleus gracilis, nucleus cuneatis that correspond to these two um, sections. And that's where they travel.... It's how it's illustrated. Like these go over here, and these go over there.

As the students discussed connections within the spinal cord, they referred extensively to the drawing. It was the point of reference for all group members and an opportunity for them to reformulate their knowledge. This artifact that the students constructed both represented their understanding and was a tool for improving their understanding as they tied up the loose ends of locating the patients' neurological problems in the nervous system. The facilitator supported student thinking by calling attention to specific pathways. Throughout this phase of the drawing activity, the group monitored their understanding and sought consensus. By the end of this episode, the students constructed a new and coherent collaborative understanding, a conceptual artifact that was quite a change from their initial understanding.

These excerpts provide one view of the knowledge-building interaction. They suggest some kinds of discourse moves that are associated with knowledge building, but these only sample the PBL tutorial. A fine-grained coding of the entire tutorial discourse is useful in characterizing the discourse and can provide suggestions that about features that are indicators of knowledge building, and how that might be facilitated. In particular, we were interested in the kinds of questions and statements that were made and who was making them. A distribution of questions among the students and facilitator would suggest that the students are sharing responsibility for improving their collective understanding. Depending on the type of questions, these may indicate collective efforts to enhance the group's understanding. The facilitator's questions can support knowledge building to the extent that they support constructive processing such as monitoring the state of the group's understanding and generating causal explanations as well as helping learners identify gaps in their understanding.

Questions

We expected the facilitator to ask more of the long-answer questions, as they required students to do more in-depth processing while elaborating a causal understanding of the underlying patient problem. In addition, we expected to see many questions that reflected the facilitator's ongoing monitoring of the group learning process. To the extent that the students had internalized the questions that the facilitator modeled, they should be asking these kinds of questions themselves as well. The students were expected to ask a lot of feature specification questions as they constructed a joint problem representation. Students were expected to ask a substantial number of questions indicating that they were engaged in constructive processing. The meta questions were expected to be the major category for the facilitator if he were functioning as the guide for the learning process.

The distribution of questions is shown in Figures 2–4. Because these were experienced PBL students, they were also expected to generate a substantial number of metacognitive questions, which indeed they did. A total of 809 questions were asked, 466 (57%) by the students and 343 (43%) by the facilitator. Of the student questions, 49% were short-answer questions, 11% were long-answer questions, and 41% meta questions (see Figures 2, 3, and 4, respectively). Of the short-answer questions, the students' (S) modal question type was to elicit the features of the patient's illness from the PBLM, for example when Jim asked "Does it say anything about medications?" Of the facilitator (F) questions, 11% were short-answer questions, 13% were long-answer questions, and 75% were meta questions. When the facilitator asked short-answer questions, they were often used to focus students' attention. Long-answer questions often asked the students to define what they had said or interpret information; for example, when the facilitator asked the student "But I mean what produces the numbness at the bottom of the feet?" Meta questions were the dominant mode for the facilitator as he asked the students to evaluate one of their hypotheses, as in, "Well yeah, multiple sclerosis. How about that? How do you feel about that . . . ?" These questions also include monitoring the group dynamics as he asked, "So Megan, do you know what they are talking about?" None of these meta questions were evaluative. The facilitator asked comparatively few content-focused questions.

The distribution of question types differed for the facilitator and the students and also differed across the two sessions. As Figures 2–4 demonstrate, there were more questions asked in the first session than in the second session. This change in distribution makes sense in that the goal in the first session was to understand

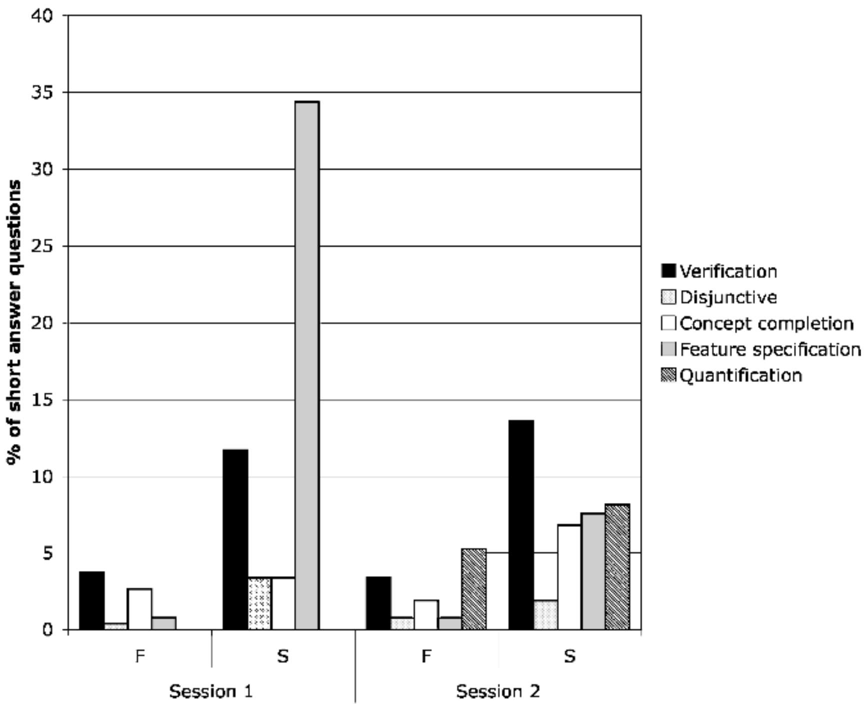

FIGURE 2 Distribution of short-answer questions by facilitator (F) and students (S). Note: The total number of 265 short-answer questions formed the base for all percentages.

the case, identify the limitations of the group's collective understanding relevant to the case, and begin to generate hypotheses that would guide their knowledge-building activities. The major type of question for the facilitator was the meta category. Many meta questions were monitoring questions that helped the group make progress in their problem solving. At the beginning of session 2, Jonathan began to report a summary of the case and the students' thinking thus far. He concluded with "... Right now, we're our differential list includes particularly a vitamin B12 deficiency. We've discussed um, also neurosyphilis or some other uh CNS injuries." At this point the facilitator noted that there were hypotheses suggested (neurosyphilis and B12 deficiency) that were not on the hypothesis list at the end of the first session and flagged this anomaly by asking "Is this, is this a new hypothesis list that you have?" Several students concurred that indeed it was. The facilitator continued to help the group plan their activities by asking "Why, why don't we look at the old one first and see what you want to do with it before we go on to the new one?" This query lead to the group's moving into an evaluation of

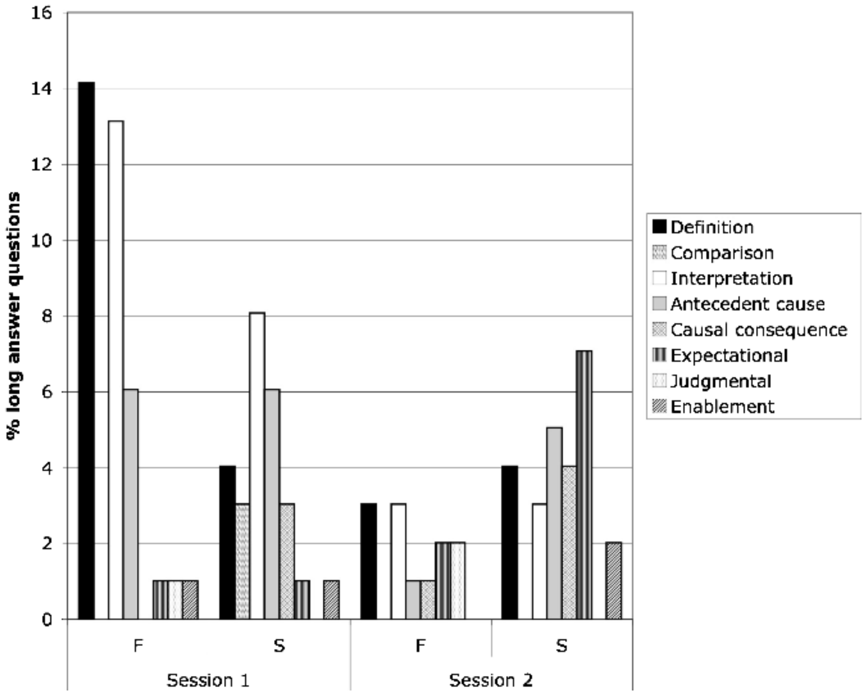

FIGURE 3 Distribution of long-answer questions. Note: There were no example questions asked so these are not represented. The total of 99 long-answer questions, was the base for the percentages.

their hypothesis list, bringing in the research from their SDL. Later in the second session, another monitoring question, "What are your leading hypotheses?" led to the extended knowledge construction discourse pattern presented earlier, when Donna noted that B12 deficiency could have caused the patient problem, with which Jim concurred. Then Donna asked if anyone found out about how B12 deficiency works. This question was followed by an episode in which students discussed causes, effects, and treatment of this problem.

Another important kind of meta question was related to SDL. In the first session, the facilitator paid more attention to SDL than in the second. For example, the students were having a vague discussion of nerve tracts, and the facilitator encouraged them to commit to a specific learning issue when he asked, "So what's, what's the learning issue, what are you stating the learning issue?" The facilitator did not often ask about SDL during the second session although it is notable that the students continued to ask these questions in both sessions as they

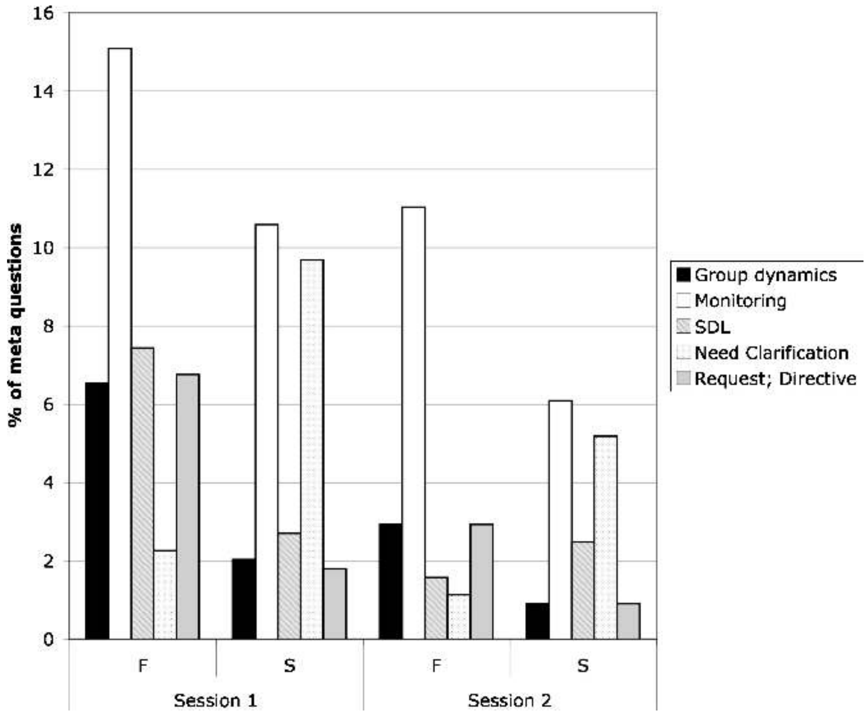

FIGURE 4 Distribution of meta questions. Note: There were a total of 444 meta questions, which formed the base for the percentages.

took a critical stance toward their own knowledge and what they learned through their SDL activity.

The second most frequent kind of facilitator questions were in the long-answer category. He asked more than twice as many of these questions in the first session compared with the second. This difference was largely because the definition questions prevalent in the first session were almost absent in the second session. These questions were often used to initiate a “knowledge display unit” (Koschmann, Glenn, & Conlee, 2000). These are topic-delimited segments of discourse in which participants raise a topic and one or more members display their understanding of that topic to the group. These segments often conclude with generation of a learning issue as students realize that they do not really understand the concept and need to learn more. By asking the students to define what they are discussing, the facilitator encouraged them to elaborate their thinking and/or realize the limits of their understanding as when students were going around the table and generating hypotheses early in the first session and Jim offered his hypothesis:

Jim:	. . . One that I have that I don't know much about except for the fact that uh, it involves interference with sensory and motor. So if she has a complaint of motor, we can ask her. . . . Uh is it peripheral neuritis? I just ran across it . . . the other night. And I don't know any mo, much more than that, so don't ask. (background laugh) [Jonathan, the scribe, writes on board under "HYPOTHESES peripheral neuritis"]
Facilitator:	Well, what do you know about it?
Jim:	That it interferes with uh sensory and motor.
Cheryl:	Well a neuritis would be an inflammation of the nerve so you do, you know that much, but . . .
Jim:	And it's, and it's uh peripheral so it wouldn't be, I wouldn't think they're talking about any cranial nerves.
Megan:	Is it related to any disease state, diabetes or anything, can it be? Or is it something else . . .
Jonathan:	I just briefly ran across it the other night.
Donna:	So might that be a learning issue we can, we can take a look at?

Here, the student offered a hypothesis; the facilitator asked him what he knew about it (a definitional question). As the students talked around their fuzzy understanding, one of the students, Donna, asked a SDL question regarding whether the proposed hypothesis should go up as a learning issue. This segment concluded with the scribe writing it on the board as a learning issue and the students moved on to another hypothesis. This simple question helped the students elaborate as much as they were able with their current understanding. It also helped them realize the knowledge limitations that they needed to address. Similar functions were served by the interpretation questions, which put issues on the table that the students would address in their SDL. On both days, the facilitator asked questions that scaffolded students' focus on creating causal explanations for the patient's problem with the causal antecedent, causal consequence, and enablement questions.

The facilitator used short-answer questions least often—these tended to be verification questions that were used to focus attention or to be sure that everyone understood. For example, after a student offered a hypothesis about alcoholic neuropathy and a justification for that the facilitator asked "So alcoholic neuropathy is direct damage to nerves, by the alcohol?" Concept completion questions, a major type of question that teachers use as part of IRE discourse in a traditional classroom, were only rarely asked (3.49% of the total questions asked).

Note that the students drastically reduced the number of feature specification questions by the second session—they constructed a representation of the problem and were eliciting further features only as they were trying to map their leading hypotheses to patient information. In comparison, the students asked the same number of long-answer questions in the second session as in the first, but the nature of the questions they asked changed. In Session 1, they often focused on interpreting individual signs and symptoms in addition to asking questions about what might cause those symptoms, whereas in Session 2, the focus on cause remained but the students asked more expectational questions. One reason for the Session 2 drop in meta questions is that they were no longer planning their SDL in the second session. Aside from a brief discussion of resources that students used in their independent research, this was no longer a focus. Instead, on the second day students focused on refining and elaborating their ideas. The large number of questions students asked provides an indicator that they were taking responsibility for their own learning as they engaged in knowledge building.

Statements

To the extent that students were taking responsibility for increasing their collective knowledge, they should have been building on each other's ideas and monitoring their thinking. Modifications, agreements, and disagreements would be characteristic of knowledge building as they negotiated a fit among their ideas and worked at transforming, refining, and improving their collective knowledge. If students took much of the responsibility for learning, then it is reasonable to expect that the students would have done most of the talking. Moreover, if knowledge were being collaboratively constructed, the students' statements should have been in response to previously introduced ideas. The facilitator should have been offering few, if any, new ideas and making statements that were in the metacognitive category, centered around monitoring the group's progress in problem-solving and SDL.

The results indeed suggested that students were taking collaborative responsibility and engaging in collaborative knowledge construction. The facilitator made a total of 243 statements (6% of the total) and the students made a total of 3763 statements (94%). The distribution of statement types is shown in Figures 5 and 6. Clearly, the students were doing most of the talking. The facilitator made few statements, rarely offering new ideas (only 3 overall, 2% of the total facilitator statements) or modifying existing ideas (21 such statements). The facilitator was most likely to offer a comment monitoring the group's progress or encouraging students to consider when a poorly elaborated idea might become a learning issue, as demonstrated by the 66 (27%) meta statements in session 1 and 102 (42%) such statements in session 2. Both the metacognitive questioning and statements helped support the students' collaborative knowledge construction, as they built on the ideas offered by others, expressed agreement, and disagreement, and modified the ideas being discussed (Figure 5). This support was especially important in the second session when the facilitator's meta statements helped support student elaboration and causal reasoning.

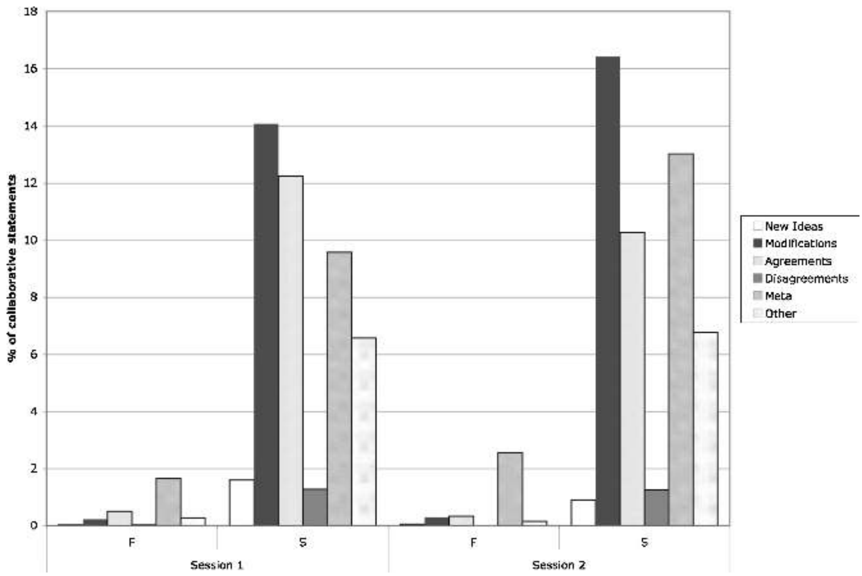

FIGURE 5 Distribution of collaborative statement types. Note: There were 4,003 statements coded that were used as the base for the percentage.

In both sessions, the majority of statements taken individually were simple statements. In the first session, the group offered many new ideas. Some ideas were initially introduced as questions, as when the students were talking about alcoholic neuropathy and Jonathan asked "is it due to a thiamine deficiency . . . "[4] Later, Megan modified the vitamin hypothesis with a simple statement: "in a patient who presents with any of these signs. There's thyroid problem possibly, a vitamin deficiency we talked about, vitamin B1 or vitamin cobalamin, vitamin B12. Um, there's also like the alcohol toxin problem. Um . . . diabetes." These were all simple assertions with very little elaboration other than a slight connection to the patient's signs.

As shown in Figure 5, the students generally worked to maintain consensus and avoid conflicts but they did modify the ideas that were circulating. It is particularly notable that in the second session, there were fewer new ideas (36 vs. 64) and more modification of existing ideas (911 vs. 727), as well as more meta statements (521 vs. 383) than in the first session. This change is consistent with refining and revising their understanding in the second session. For example, at the beginning of Session 2, prior to actually discussing the case, the students engaged in a metalevel critical discussion of the resources that they used and how helpful they were as in

[4]Thiamine is vitamin B1.

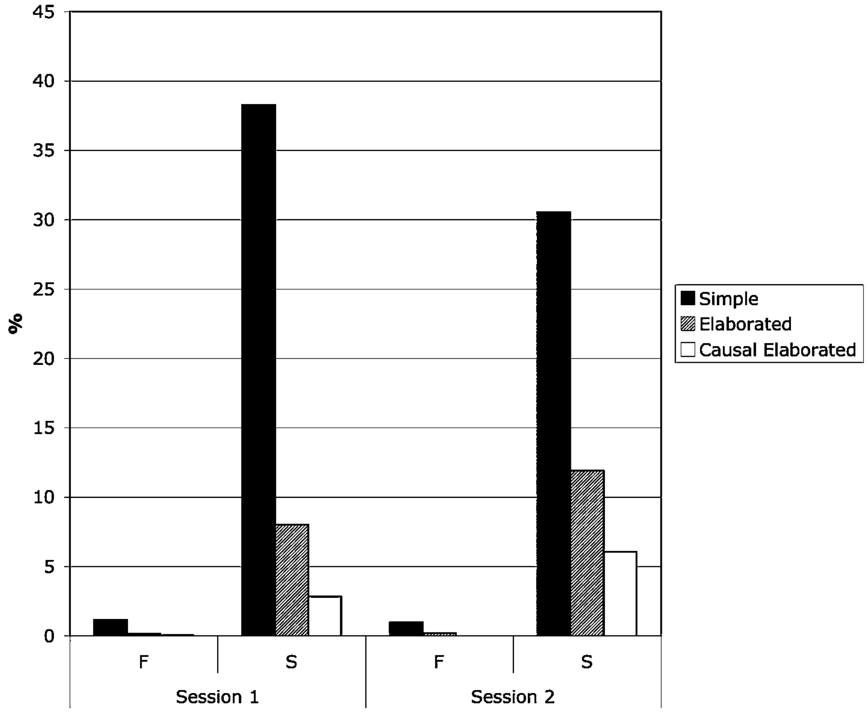

FIGURE 6 Distribution of statement complexity. Note: A total of 2,380 statements were coded for complexity and this was used as the base for percentage.

this example from Megan's report: "Um, I was actually looking for vitamin B12 deficiencies, the neurological symptoms and um, I got a few things that were very good but um, many that weren't as scientific as I would have liked them to be."

As the measure of statement complexity shows, the students engaged in more elaboration and causal reasoning in the second session than in the first as they used the knowledge they had gained in their SDL to flesh out their ideas (Figure 6). On the second day, they asked fewer questions and engaged in more explanation as they brought in the information that they had gleaned from their SDL. The number of causal elaborations more than doubled in the second session. As the discussion proceeded, Megan brought in some of the information she found about B12 and resuscitated the hypothesis that the group had actually crossed off their list (as discussed earlier and again later in Table 5b). Here Megan was modifying an earlier idea as she elaborated why Vitamin B12 deficiency is a likely explanation by mapping her new knowledge onto the patient's features. Contrast this elaboration with the simple assertion about Vitamin B12 presented earlier. Clearly she has demonstrated some learning. Donna added further to this explanation by concurring in terms of how serious this is.

Although many statements individually were simple statements, as collaborative explanations they were elaborated, often causally, over several speakers and several conversational turns. In the example in Table 5a, we show how the students' first discussion of pernicious anemia was coded and how this fine-grained coding highlights the nature of the collaborative process. As students began their discussion, the facilitator pushed them to define what they meant. This segment ended with pernicious anemia added to the hypothesis list. Note the number of simple statements coded in Table 5a—but the whole here is greater than the sum of its parts. This explanation is collaborative because four of the five students contributed different parts of the explanation. The facilitator triggered the explanation, but then different students offered pieces of the explanation about pernicious anemia, what some signs might be (neuropathies) and what alternative explanations they could rule out (poor absorption of B12 in the gut).

In session 2, the students engaged in knowledge building through more elaborated collaborative explanations. As they revised their explanation, applying what they learned from their SDL, they continued to elaborate and add causal information as the example in Table 5b demonstrates. We revisit an earlier example to use the two different grains of analysis to complement each other. After their SDL, the students revisited their hypotheses one by one, and they co-constructed explanations that continued to be elaborated. The facilitator had the students go sequentially through the hypothesis list, evaluating the evidence for each one. The next segment began with Megan's comment that explained how the symptoms of a B12 deficiency matched the patient's symptoms, thus mapping the disease to the evidence provided by the patient data. Donna added to the explanation, noting how this hypothesis is better than another one on their list. Cheryl and Jim disagreed about whether it had been eliminated as a hypothesis, but the facilitator moved the discussion forward with his "Where are we . . . " question. This move actually put the hypothesis on the active list for consideration. Cheryl added some information about the likelihood of a person like this patient having this problem and Jim brought in additional information to explain how the vitamin B12 deficiency is caused. The fine-grained coding shows how they began with agreement on an idea, worked at modifying and elaborating it, and finished the episode by monitoring their understanding.

Maintaining the Discourse: Analysis at the Level of Episodes

At first glance, it might seem as though the role of the facilitator in promoting knowledge building is trivial because of the low proportion of questions and statements generated. An intermediate grain of analysis examines how collaborative

TABLE 5a
Session One Collaborative Explanation

Utterance	*Question Code*	*Statement Code*
Facilitator: Megan does that malnutrition vitamin B cover the, the things you were talking about just a minute ago? You were concerned about there's a number of different vitamins that may be involved.	Monitoring	
Megan: I, hmmm.		Uncodeable
Facilitator: Can we just leave the, that hypothesis up?	Request/Directive	
Megan: Oh yes. I think that's fine.		Agreement Simple
Donna: Like pernicious anemia is a big one.		Modification Simple
Megan: Right. That must be the vitamin, the B.		Agreement Simple
Facilitator: What, what's pernicious anemia?	Definition	
Donna: Uh, it's a deficient, deficiency of cobalamin.		New idea Simple
Megan: Vitamin B12, cobalamin or . . .		Modification Simple
Jim: Or folate.		Modification Simple
Megan: Or folate.		Repetition
Donna: Yeah, but it's not, that's not pernicious anemia. That's a, also another macrocytic anemia.		Disagreement Simple
Megan: Pernicious anemia is specifically.		Modification Simple
Jim: Oh. You're right. That's right.		Agreement Simple
Donna: And um, you get anemia and you can also get eh, um, peripheral . . .		Modification Elaborated
Megan: Neuropathies.		Modification Simple
Donna: . . . neuropathies.		Repetition
Facilitator: Down there too?*	Verification	
Cheryl: Technically pernicious, pernicious anemia is technically just the loss, the lack of intrinsic factor.		Modification Elaborated
Donna: The loss of intrinsic factor. So you don't absorb.		Repetition Modification Simple
Cheryl: And that's [unintelligible]		Uncodeable
Donna: You don't absorb.		Repetition
Cheryl: Right.		Agreement Simple
Megan: Right. That's a good distinction. You see, we just . . .		Agreement Simple
Cheryl: As opposed to like somebody who had part of their intestine removed and can't absorb.		Modification Elaborated
Megan: Right.		Agreement Simple
Cheryl: But their ileum is gone and they can't absorb the B12. That's different than pernicious anemia, to vit, intrinsic factor.		Disagreement Simple

*The facilitator appears to be referring to the patient's chief complaint of numbness in the feet.

TABLE 5b
Session 2 Collaborative Explanation

Utterance	*Question*	*Statement*
Donna: Yeah. I, I agree with that.		Agreement Simple
Megan: Check it out.		Agreement Simple
Donna: And also I was just, happen to glance at it last night and um, 'cause I was just talking with my husband and, about the um, neurosyphilis and, and uh, the olivopontocerebellar atrophy being pretty serious and progressive and, and I was thinking that vitamin B12 wasn't so much if you treated it. But it, I was reading that it's in a lot of the neur, uh, neural deficits are irreversible.		Meta Modification Elaborated
Megan: Uh hmm.		Uncodeable
Donna: So it is, you know. It does put in my mind it's a more of a serious.		Modification Simple
Facilitator: Now you people are saying B12 all the time and yet when you say we eliminated it, you're talking about pernicious anemia, right?	Verification	
Cheryl: Well.		Uncodeable
Jim: Well no, actually we eliminated vitamin B.		Disagreement Simple
Facilitator: Ah, okay.		Meta
Cheryl: We never actually ruled out pernicious anemia.		Meta
Jim: Way up there.		Meta
Facilitator: So how are we on pernicious anemia? I want to finish up that list.	Monitoring	
Cheryl: Oh we did have it.		Meta
Megan: Well, she might not have pernicious anemia. I mean, it's possible. What we need to do is, is check.		Meta
Cheryl: Wouldn't that be the more likely though?		Meta
Jonathan: No.		
Donna: No. Well, not, not necessarily.		Disagreement Simple
Cheryl: Because she's in her seventies, the lack of intrinsic factor is more common.		Modification Elaborated
Megan: They, they often. Actually they often have atrophic gastritis, elderly people.		Modification Simple
Cheryl: That's true.		Agreement Simple
Megan: And eh, so those people even if they have intrinsic factor, cannot, still cannot absorb the vita, vitamin B12.		Modification Causal Elaborated
Donna: Yeah. One thing I read was achlorhydria.		Agreement Simple
Cheryl: Uh hmm.		Uncodeable
Donna: If they get um. That decreases the amount of cobal, cobalamin that can be absorbed because it binds to um, an R factor or something that . . .		Modification Causal Elaborated

(Continued on next page)

TABLE 5b
Continued

Utterance	*Question*	*Statement*
Megan: You cannot cleave the R binder from the transpondent.		Modification Elaborated
Donna: ... that, that competes with intrinsic factor so that it's not. Even if you have intrinsic factor, it's not affected because it can't bind with cobalamin.		Modification Elaborated
Jim: Well, that, that's exactly it. Like ninety or ten percent of the, of elderly that have a vita, vitamin B problem is due to pernicious anemia. The other ninety percent are due to, is due to the fact that, that when you take, ingest vitamin B12 it's complexed with a protein, an R protein. And they lack the ability to break that protein apart to have the vitamin B site of cobalamin free. So then it can bind to the intrinsic factor. So if they, it's not binding to the uh, if it's not breaking off, you may, you may have tons of intrinsic factor, but since it can't get a hold of it, it's like not gonna do.		Modification Causal Elaborated
Megan: And that achlorhydria that you just mentioned, that is secondary also to atrophic gastritis?	Verification	
Donna: Yeah. Achlorhydria		Agreement Simple

knowledge building is advanced at the level of larger episodes. The discourse was parsed into a total of 101 episodes, 60% initiated by the facilitator and 40% initiated by the students. In general, all students were actively engaged in the discussion (mean of 94% for facilitator-initiated episodes and 90% for the student-initiated episodes). The facilitator-initiated episodes tended to be longer than the student-initiated episodes (49.9 and 34.3 turns, respectively). The quantitative data and inspection of the episodes suggest that the facilitator-initiated episodes went deeper than the student-initiated episodes. Regardless of who initiated the episode, the students often had long runs of discourse without interruption by the facilitator (a mean of about 20 was the maximum length of consecutive runs of student talk). This pattern suggests that the facilitator, despite what appear to be limited contributions, often served to catalyze the collaborative knowledge building process, but the students also shared this responsibility. The kinds of initiating moves were quite different depending on who initiated. Of facilitator initiations, 62% were questions or statements related to monitoring or group dynamics. These initiations often served the purpose moving the students forward, agreeing on common understanding, working with hypotheses and generally, maintaining the agenda. These initiating moves might have invited new hypotheses or asked the group to evaluate old ones. They helped move things along as the facilitator had students summarize, report on learning issues, and sometimes move them forward when they were engaging in a circular discussion. Of the student-initiated episodes, 35% of initiations were meta statements or monitoring questions. The student initiations tended to be more specific as they called attention to a particular symptom, a test that might otherwise be forgotten, or to put out specific proposals for what should be done next. They tended to be more content-focused, either clinical or basic science. It is noteworthy that both facilitator- and student-initiated episodes were often used to involve students who needed an opening. This analysis suggests that the discussion remained student-centered but the facilitator had an important catalyzing role.

DISCUSSION

In this PBL tutorial, both the students and facilitator engaged in discourse that improved the group's collective understanding. We demonstrated that in knowledge-building discourse, the students and teacher share responsibility for creating a conceptual artifact—in this case, a causal explanation. We have shown this through the use of multiple methodologies that may prove useful to other investigators as they examine how other instances of knowledge building are similar to what we have observed in PBL, as well as how they differ.

The discourse is different from the typical IRE classroom frame in which the teacher directs the classroom. The students asked more than half the questions and generated all the ideas under discussion. The facilitator asked many open-ended questions, offered few ideas, and never made evaluative comments, other than occasionally indicating that an idea students were working with might need to be a learning issue. In this way, the teacher helped support progressive discourse (Wells & Arauso, 2006). The students actively monitored their thinking, spent a great deal of time in the first session constructing a rich problem representation, and subsequently constructed a shared understanding, as demonstrated by both their questioning and explanation behaviors. They built on each other's ideas and worked hard to achieve consensus as they improved their collective understanding, consistent with other examples of knowledge building (e.g., Engle & Conant, 2002; Hogan et al., 1999). The facilitator helped create the affordances for this kind of constructive discourse through open-ended questions, subtle attention focusing techniques, and other strategies (Hmelo-Silver & Barrows, 2006).

This discussion met the requirements for knowledge building as the students collaboratively constructed a causal explanation, a kind of conceptual artifact. This conceptual artifact resulted from the group's engagement with a knowledge problem. The students actively worked on improving the coherence and quality of their collective knowledge. Improvement was demonstrated by the change in their understanding over the two sessions. The students made their thinking visible, modifying each other's ideas and discussing their information resources at length as they negotiated among the different ideas in the group and engaged in knowledge-building discourse. All students took responsibility for advancing the group's understanding as demonstrated in both the qualitative and quantitative analyses.

The facilitator used a variety of questioning tactics to help support this knowledge-building discourse. As the literature suggests, these questions served a variety of functions (Burbules, 1993; Graesser & Person, 1994). The major type of questions that he asked fell into the *meta category* and helped the group monitor their progress and focus on their SDL. Some of the *long-answer questions* served meta functions as well. For example, *definition* and *interpretation* questions, particularly in session one, helped students see the limits of their understanding. Other questions focused on cause and provided models of the kind of causal reasoning that is needed for understanding the case. By pushing the students to explain their thinking, the facilitator helped them problematize their ideas. Short-answer questions, common in traditional classroom teaching, were used judiciously by the expert facilitator to help focus student discourse in a relevant conceptual space. The facilitator combined these questioning tactics into the larger strategies that serve a variety of knowledge-building goals such as causal explanation, metacognition, SDL, and group negotiation (Hmelo-Silver & Barrows, 2006). Moreover, the facilitator often catalyzed collaborative knowledge building as he helped move the group along and pushed them to think deeply.

Both the facilitator and students adapted their discourse moves as their knowledge building efforts progressed. Knowledge-building discourse is characterized by building a deep understanding of a problem, questions that promote deep thinking, and continual efforts to refine and improve ideas as this PBL group did. The facilitator engaged in a great deal of questioning early on, questions that often elicited knowledge displays that helped students realize what they needed to learn more about. Students initially asked many questions that helped them understand the problem, generating most of their new ideas on the first day and building on these subsequently. The facilitator prompt to draw a diagram led to an extended knowledge-building episode that became an occasion to negotiate a rich, common understanding. Throughout, the discourse remained productive as the students shifted their discussion from the broad list of hypotheses to a detailed causal explanation that accounted for the patient's signs and symptoms.

Important questions remain: Can some of these facilitation techniques be used to scaffold collaborative knowledge building in other settings? Can some of these techniques be offloaded onto cultural tools and participant structures that might help extend the teacher in larger classes? These techniques can be used provide models for orchestrating collaborative knowledge building. Additional studies of facilitation are needed to understand what general techniques are useful across different settings and what kinds of adaptations may be required. Nonetheless, we believe that this is an important beginning in understanding how knowledge building is actually accomplished.

Although these are academically successful, highly motivated medical students and are not representative of K–12 populations, the analysis of an expert facilitator has important implications for training novice teachers to create knowledge-building classrooms. These results provide suggestions for conversational moves that facilitators might make and representations that could embody the learning goals and strategies that an expert facilitator uses. For example, some of this scaffolding might provide prompts for groups to use at different parts of the PBL process. It shows how different kinds of teacher questions can be used for different goals. In IRE discourse, a definition question may be used to elicit a knowledge display for evaluation but it can serve a different function in a student-centered classroom by helping students realize the limits of their understanding. This study demonstrates how important it is for teachers to provide models of questions that promote deep reasoning and metacognition that students can appropriate as well as how teachers can share responsibility with students for their learning. These questions provide learning opportunities that lead to knowledge building as several of the discourse examples demonstrated. Finally, the use of both formal (the structured whiteboards) and informal (drawing flowcharts and diagrams) representations can provide opportunities for knowledge building and integration.

CONCLUSIONS

In this article we demonstrated how an expert facilitator and students in a PBL tutorial engage in collaborative knowledge building. The PBL learning process requires the students, through collaborative discussions, to recall and use what they already know to analyze and understand the problem at hand as well as possible, to recognize what they need to learn to build a better understanding of the problem, to find and use appropriate sources of information for that learning, to apply their new learning to their understanding of the problem, to summarize what they have learned, and then to evaluate their learning performance. The student interactions are characterized by questioning and by a give-and-take that involves creating, refining, and improving their collaborative explanation. The facilitator's task is to promote collaborative knowledge building among students in a manner that is student-centered, and encourages students to become responsible for their own learning. The facilitator supports the group discourse largely through the use of open-ended metacognitive questioning that serve as scaffolds that are faded as the questions are internalized by students (Collins et al., 1989; Hmelo-Silver, 2006). This strategy provided an environment that encouraged students to also use high-level questioning as they worked together in their collaborative learning. It provided opportunities for students to engage in knowledge building as their understanding is constructed, refined, and transformed. Helping teachers and students learn to ask the right kinds of question and build on each other's thinking may be a key to orchestrating knowledge-building discourse but we need to further examine how different participant structures and teacher scaffolding support knowledge-building practices in other contexts.

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