Problem-Based Learning: Using Ill-Structured Problems in Biology Project Work

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ABSTRACT: This case study involved year 9 students carrying out project work in biology via problem-based learning. The purpose of the study was to (a) find out how students approach and work through ill-structured problems, (b) identify some issues and challenges related to the use of such problems, and (c) offer some practical suggestions on the implementation of problem-based project work. Data sources included observation and field notes, students' written documents, audiotapes and videotapes of students at work, and student interviews. The findings showed that several students initially experienced difficulties in identifying a problem themselves but after discussing with family and friends, were able to overcome this initial barrier and subsequently formulated personally meaningful problems for investigation. The ill-structured problems stimulated students to pose questions which charted their courses of action, leading to independent inquiry. Students were led to investigate multidisciplinary elements beyond the boundaries of typical school science, and also learned about different modes of inquiry. The issues and challenges identified included identifying a problem for investigation; asking questions to negotiate the learning pathway; deciding what areas to pursue, given a multitude of possibilities; and figuring out how to extract relevant information from the available mass. Implications of the findings for instructional practice are discussed. © 2005 Wiley Periodicals, Inc. *Sci Ed* **90:**44–67, 2006

INTRODUCTION AND BACKGROUND TO THE PROBLEM

The education system in Singapore is largely examination oriented. At the opening of the 7th International Conference on Thinking held in Singapore in 1997, the prime minister

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noted in his speech that other than being motivated by the reward of getting good grades, the "passion [for learning] is generally lacking among our students, including many among our most able" (Goh, 1998). It was recognized that changes had to be made in the education system to reverse the trend of producing students who were concerned only with getting good grades, and rote-learners who would not be ready to meet the demands of the knowledge-based economy. Instead, students must be encouraged to go beyond the memorization of facts, to think critically and creatively, and to apply their knowledge in problem solving in new and unfamiliar contexts.

In response to this concern, as well as to recent local and global reforms in education that emphasize inquiry and self-directed learning, the Ministry of Education in Singapore launched its vision of "Thinking Schools, Learning Nation" in 1998. As part of this vision, the school curricula were revised to encourage more thinking, questioning, and independent learning on the part of students. As Goh (1998) noted, "Thinking Schools must be the crucibles for questioning and searching, within and outside the classroom to forge this passion for learning among our young."

One recent initiative implemented to promote active learning and higher order thinking in our students is collaborative project work. This is consistent with the goal of inquiry-based science instruction to engage students in the investigative nature of science through hands-on activities, and problem solving. However, in the actual implementation of project work, the essence of inquiry may get diluted, displaced, or distorted, if students merely follow prescribed procedures, usually without questioning, to solve well-defined problems that are given by the teacher and that have expected solutions. In such cases, where the activities are highly structured, procedures are specified, and results are known beforehand, students are often unable to relate the activities to everyday experiences (Marx et al., 1997) and to think deeply about the underlying science concepts. Hence, such activities promote hands-on "doing science" but not necessarily a minds-on approach to learning (Tobin, Tippins, & Gallard, 1994). To infuse more authentic inquiry in science projects, one can use problem-based learning where students generate their own problems which are often realistic, ill structured, and precede learning.

INQUIRY-BASED SCIENCE INSTRUCTION

A main goal of science education is to promote scientific thinking in students. To this end, teachers are encouraged to engage students in inquiry-based tasks which involve the cognitive processes that scientists use when they conduct research. These include generating a research question, designing a study to address this question, making observations, explaining results, developing theories, and studying others' research (Chinn & Malhotra, 2002). Participation in inquiry activities encourages students to pose questions, propose hypotheses, make predictions, use tools to gather and analyze data, generate inferences in light of empirical evidence, construct arguments, communicate their findings, and to use a broad array of reasoning strategies that involve critical, creative, causal, and logical thinking (Olson & Loucks-Horsley, 2000; Minstrell & van Zee, 2000).

Besides helping students to develop conceptual understanding of science content and the relevant process skills, inquiry-based instruction also aims to foster an epistemological understanding of the nature of science. There are different levels of inquiry, depending on the degree to which teachers provide structure for an investigation. Inquiry may thus be "guided" (partial) or "open" (full) (Olson & Loucks-Horsley, 2000) depending on how much autonomy the student has in posing the research question, designing the investigation, and interpreting the results.

Zion et al. (2004) characterized open inquiry as being dynamic and iterative, where learning is a process of continuous and renewed thinking that involves flexibility, judgment, and contemplation, in response to changes that occur in the course of the research. They also emphasized the importance of procedural understanding of the concepts of evidence, as well as affective aspects such as curiosity, frustration, surprise, perseverance, and having to cope with unexpected results.

Although many science programs espouse inquiry as a pedagogical approach to enhancing learning, there are difficulties with enacting inquiry in science classrooms. These include (a) the absence of a clearly formulated philosophy of the nature of scientific inquiry in science policy statements and curriculum documents produced by local education authorities, (b) teachers' lack of first-hand experience with authentic science inquiry during their education, (c) teachers' lack of pedagogical content knowledge and discursive skills to support inquiry, (d) accountability pressures and teachers' efficiency beliefs in having to cover science content to help students prepare for high stakes standardized tests, (e) lack of resources that support inquiry (e.g., appropriate textbooks and technical support), (f) lack of monetary and human resources in developing experiments, designing assessment tools, and in the professional development of teachers, and (g) students who may not have the motivation, knowledge, and skills to engage in inquiry (Abd-El-Khalick et al., 2004; Rowell & Ebbers, 2004).

Contemporary inquiry approaches to science instruction advocate having students work through "investigations beginning with authentic relevant questions and problems involving 'fuzzy' data sets and building to the development, revision, and redevelopment of scientific models and explanations" (Abd-El-Khalick et al., 2004, p. 413). These include project-based science (Krajcik, Czerniak, & Berger, 1998), technology-supported science programs (e.g., Linn & Hsi, 2000), and problem-based learning.

PROBLEM-BASED LEARNING

Problem-based learning (PBL) is an innovative curricular approach that was originally developed in medical school programs (Barrows & Tamblyn, 1980), and later adapted for use in elementary and high school settings. In PBL, problems act as the stimulus and focus for student activity and learning (Boud & Feletti, 1991). Students learn while searching for solutions to problems and in the context in which knowledge is to be used. Unlike traditional teaching approaches which introduce problems only after students have acquired the relevant content knowledge and skills, problems are introduced at the beginning of a unit of instruction. This reverse "problem-first" approach in PBL helps students to understand why they are learning what they are learning (Gallagher et al., 1995).

Characteristics of PBL include using an ill-structured problem to guide the learning agenda, having the teacher act as a metacognitive coach, and students working in collaborative groups. Ill-structured problems are those where the initial situations do not provide all the necessary information to develop a solution, and there is no one correct way to solve the problem. As facilitators of learning, teachers acquaint learners with new ideas or cultural tools, to support and guide students as they make sense of these (Driver et al., 1994), and to scaffold students' ideas in the zone of proximal development (Vygotsky, 1978). Because students work on a problem that is situated in real-life contexts, they are better able to construct links between school science and the science required to solve real-world problems (Yager & McCormack, 1989). Students identify learning issues pertinent to the problems and ask questions related to these issues. They make their own decisions about what directions to take in their investigations, what information to gather, and how to analyze and evaluate this information.

Four design principles appear to be especially important in the implementation of PBL instruction: (a) defining learning-appropriate goals that lead to deep understanding, (b) providing scaffolds that support student learning, (c) ensuring opportunities for formative self-assessment and revision, and (d) developing social structures that promote participation (Barron et al., 1998). Providing learning-appropriate goals helps students to understand the how and why of a project, while frequent opportunities for reflection promote the thinking behind the doing.

PBL in collaborative group contexts is consistent with the theory of social constructivism which views learning as being mediated by the use of language, knowledge as being socially co-constructed, and problem solving as a process that is not internal to the individual but instead grounded in social practice (Hennessy, 1993; Hodson & Hodson, 1998; Howe, 1996; O'Loughlin, 1992; Vygotsky, 1986). This approach to learning is also consistent with the ideas of distributed cognition (Pea, 1993) as well as situated cognition (Brown, Collins, & Duguid, 1989; Hennessy, 1993, Wenger, 1998) where students are engaged in discursive practices in the context of relevant tasks and participating in communities of practice.

The view that cognition is social, distributed, and situated in nature implies that students have "funds of knowledge" (Moll et al., 1992) that they bring to bear on their classroom learning. This refers to the knowledge and skills that students can draw on from their families, household functioning, culture, and social networks of exchange in the community.

LEARNING THROUGH ILL-STRUCTURED PROBLEMS

The kinds of problems that students encounter in school have little to do with the problems that they need to solve in everyday settings (Lave, 1988; Roth & McGinn, 1997). Whereas school problems posed by textbooks and teachers are typically well structured, the kinds of problems that students face in real-world situations are mostly open and ill structured.

Unlike well-structured problems that have convergent solutions, and engage the application of a limited number of rules and principles within well-defined parameters, ill-structured problems possess multiple solutions, solution paths, and fewer parameters which are less manipulable. They also contain uncertainty about which concepts, rules, and principles are necessary for the solution, or how they are organized and which solution is best (Jonassen, 1997). One or more aspects of the problem situation (e.g., initial state, goal state, and the set of operators for moving from the initial state to the goal state) are not well specified; the information needed to solve the problem is not contained in the problem statement (Chi & Glaser, 1985) or the constraints are unstated (Voss, 1988; Voss & Post, 1988). This contrasts with well-structured problems where all elements and processes required for the solution are knowable and known (Kitchner, 1983), and where the solutions require using logical, algorithmic processes such as means-end analysis in which the problem solver consistently compares the current problem state with the goal state (Greeno, 1978).

Ill-structured problems are also inherently interdisciplinary (Gallagher et al., 1995), requiring the integration of several content domains. Students identify problems that are not defined by disciplines but by interest. This allows for many and varied examples of how different disciplines approach a single subject and interact during problem solving. As Pea (1993) pointed out, "part of knowing how to learn and solve complex problems involves knowing how to create and exploit social networks and the expertise of others, and to deftly use the features of the physical and media environments to one's advantage" (p. 75).

Goel (1992) compared the task environments and problem spaces of well-structured and ill-structured problems from a cognitive science perspective. There are a number of substantive differences in the task environments. First, while the constraints in well-structured problems are logical or constitutive of the task, those of ill-structured problems are mainly nomological; many of them are social, economic, and cultural. Second, ill-structured problems are more complex and typically take longer to solve. Third, for well-structured problems, the "lines of decomposition" are determined by the logical structure of the problem, whereas those for ill-structured problems are determined by the physical structure of the world, practice within the community, and personal preference. Fourth, one finds logical interconnections in well-structured problems, but the interconnectivity of parts in ill-structured problems are contingent, giving considerable latitude to the problem solver in determining which ones to attend to and which ones to ignore.

With regard to problem space, there are also a number of differences. First, the "stopping rules and evaluation functions" for well-structured problems are determined by the structure of the problem. However, for ill-structured problems, these decisions are based on personal preferences and experience, standards, and expectations, because there are no right and wrong terminating states and there are few logical constraints. Second, while well-structured problems map the initial state onto the goal state, the constraints for ill-structured problems are manipulable because the problems are incompletely specified. Thus, it is possible for persons working on the problem to change the problem parameters so as to change the start state to one which better fits their knowledge, experience, and expertise. Alternative solutions and pathways can emerge through incremental transformations of a few key ideas.

When learning from ill-structured problems, students engage in a reflective conversation with the elements of the problem situation, which is a dialectic process. They are required to define the problem, recognize the divergent perspectives and multiple representations of the problem, determine what information and skills are needed to solve the problem, and synthesize their understanding of the problem. In doing this, they have to (a) articulate the problem space and contextual constraints, (b) identify and clarify alternative opinions, positions, and perspectives of stakeholders, (c) generate possible solutions, (d) assess the viability of alternative solutions by constructing arguments and articulating personal beliefs, (e) monitor the problem space and solution options, (f) implement and monitor the solution, and (g) adapt the solution. Solving ill-structured problems is largely an iterative and cyclical process (Jonassen, 1997).

The model for solving well-structured problems is based on information-processing theories of learning, while the model for solving ill-structured problems relies on (a) the theory of ill-structured problem solving as described above (Jonassen, 1997), (b) cognitive flexibility theory which conveys problem complexity by presenting multiple perspectives and opinions (Spiro et al., 1987, 1988), and on (c) constructivist and situated cognition approaches to learning (Brown et al., 1989). As Roth (1994) pointed out, "From a constructivist view, such [ill-structured] problematic situations provide favorable conditions for learning, because the problem solver is facing conditions for which no known procedures are available" (p. 216).

Shin, Jonassen, and McGee (2003) found that solving well-structured and ill-structured problems engaged slightly different skills. Domain knowledge and justification skills were required for solving both kinds of problems. However, solving ill-structured problems further required students to possess skills related to regulation of cognition, including planning, monitoring, and re-evaluation of goals. This was because ill-structured problems, being ambiguous by nature, required the consideration of alternative goals and solutions, and learners needed to keep track of the solution activity, noting their limitations, and the effects of their efforts. To solve ill-structured problems, problem representation, justification, monitoring, and evaluation skills are the primary requirements (Voss & Post, 1988). In particular, justification skills are paramount because the solvers must generate a viable, defensible, and cogent argument to support the problem solution.

PURPOSE AND SIGNIFICANCE OF STUDY

This study employed PBL in project work where students formulated their own problems, identified learning issues based on the problem, and structured their inquiry around self-generated questions. We use the term "problem" to refer to a broad, overarching, ill-structured problem statement that presents a scenario written by the students in the form of a narrative. A "question" refers to any query posed by students in an interrogative form.

The purpose of the study was to investigate how students handle ill-structured problems, identify some issues and problems related to the use of such problems, and offer some practical suggestions on the implementation of problem-based project work in science. The specific research questions were

1. How does the ill-structured nature of a problem in a PBL context influence the way students approach and work through the problem?
2. What are some issues and problems associated with the implementation of project work through ill-structured problems in PBL?
3. How can these issues and problems, as exemplified in this study, provide us with insights about how teachers can guide students' learning when using ill-structured problems in project work?

The findings of this study would shed light on how ill-structured problems impact on the way students approach their learning tasks. The issues and problems encountered, as illustrated in this study, can also enhance our understanding of how to better design, manage, and implement project work through PBL. Specific examples of ill-structured problems used in this study can serve to illustrate how problem-based project work may be carried out in the classroom. As teachers are still largely inexperienced in this area, the findings from this study would provide useful information related to the implementation of PBL.

Our previous studies reported on students' inspirations for their self-identified problems in PBL and the kinds of questions asked (Chin & Chia, 2004a), as well as how students reacted to this PBL approach (Chin & Chia, 2004b). This study extends our earlier work by focusing on how ill-structured problems may be used in project work.

DESIGN AND METHODS

To investigate how ill-structured problems in a PBL context influenced the way students worked through their problems in project work, an interpretive case study (Merriam, 1998) of a year 9 biology class (15-year olds) was used. This design was considered most appropriate as it would allow us to gain an in-depth understanding of the transactions and dynamics that occurred in that context. A within-case analysis was used where groups of students were considered as subunits to be studied within the case.

The study, which focused on the theme "food and nutrition," took place at an all-girls secondary school and lasted 18 weeks. Besides studying biology, the students also studied chemistry and physics as separate science subjects. In their lower grade levels, the students studied general science and so had some basic content knowledge of the essential concepts related to food and nutrition. The second author was their biology teacher. The class of 39 students worked in nine groups of four to five, each with an elected group leader. The students were used to working in small groups, and were free to form their own groups which were heterogeneously mixed in terms of ability and racial composition.

Each group worked on a project topic of their choice related to the given theme. As the students were more familiar with traditional project work involving structured tasks, the present open-ended investigative project was a novel experience for them. The project, which was implemented as an enrichment activity, was infused into regular lessons that comprised a mixture of direct instruction, laboratory practical work, and group discussions. One 35-min period per week was specifically set aside for students to work on the project. During the remaining four periods each week, the teacher integrated students' project work ideas and findings into her lessons which focused on enzymes, nutrients and classes of food, a balanced diet, nutritional deficiency diseases, animal nutrition, and plant nutrition. For example, at different points in the lessons, teams of "expert researchers" who investigated the different aspects of food and nutrition, were asked to share their knowledge of the topics and issues that were being raised. These included food tests, dentition, as well as the relationship between diet, weight, and health. The rest of the students were encouraged to raise related questions and the teacher facilitated the discussions.

Stages of Implementation

Before the students embarked on their projects, the teacher briefed them on the aims and objectives of the project. These included applying critical and creative thinking skills, improving their communication skills, fostering collaborative learning skills, and developing self-directed inquiry and lifelong learning skills. Each group was also given a file containing a number of information sheets and planning forms to guide them in documenting their ideas. Besides meeting the teacher during curriculum hours, the students were also in regular contact with her via email outside class. Students also met together outside curriculum time to work on their projects.

In carrying out their project work, the students went through five consecutive stages adapted from Sharan and Sharan (1989): (1) identifying the problem to be investigated, (2) exploring the problem space, (3) carrying out the scientific inquiry, (4) putting the information together, and (5) presenting the findings, teacher evaluation, and self-reflection.

In stage 1, the students familiarized themselves with some issues related to "nutrition" by reading and discussing case studies and newspaper articles on topics such as people's diets, weight loss, health issues, dietary, and herbal supplements. They then identified the problem that they wanted to investigate. During the first week, they wrote down their ideas and questions individually into problem logs and mind maps, and even brought them home. The teacher then showed them some examples of how to frame topics into ill-structured problems in the form of a written narrative, and which was open ended and based on a real-life context. The groups shared their individual questions and decided on a topic that was of interest to most of the members. They then jointly formulated their problems in the form of a little narrative story that related to their chosen topic and that encapsulated most of what they were interested in. In writing their problems, the students were encouraged to take on real-life problem-solving roles.

In stage 2, the students identified learning issues related to the problem and organized them around three focus questions (Gallagher et al., 1995) using a "Need-to-Know" worksheet.

The questions were (a) What do you know?, (b) What do you need to know?, and (c) How can you find out what you need to know? The students recorded their ideas and questions onto this worksheet regularly as a group. They also identified the resources that they needed and the type of tasks they had to undertake, to solve their problem.

The students were introduced to the various possible sources of data and information, and taught how to distinguish between primary and secondary sources. For example, primary data sources would comprise laboratory experiments, questionnaires, and interviews; while secondary sources would include newspaper reports, books, and Web sites. The students were encouraged to collect information from as many sources as possible to enhance the validity of their findings. Upon seeing that many students relied heavily on the Internet for information, the teacher also taught the class how to evaluate the quality of Web site resources. Students were also told that all information gathered from print and digital sources had to be acknowledged in a bibliography, and were shown how to write one. In groups where students planned to conduct interviews as part of gathering information, the students had to plan and write their questions first on the “Planning for an Interview” form.

In stage 3, the students collected data to answer their own questions. The teacher set up an Internet forum page (“e-circle”) for students to consult a panel comprising a doctor, a dentist, a nurse, and a medical research worker. Students used this platform to ask questions related to their research. Some of the groups used the science laboratory to carry out their investigations. Others consulted experts, went on field investigations, conducted surveys and interviews, and looked up information from print and electronic resources using both library research and the Internet.

In stage 4, the students reported on what they had done, completed further Need-to-Know worksheets, and planned for further tasks which served to track the progress of their inquiry. They documented their questions, filled in “Learning Log and Project Tasks Allocation” forms where they recorded what they had learned at each step of the project, and planned ahead for the next step in their inquiry. This helped them to review and consolidate the information gathered, as well as to monitor their own progress.

In stage 5, each group gave a 15-min oral presentation on what they had learned about their project topic, and this was followed by a question-and-answer session. All the presentations were videotaped. The groups used technology-based multimedia modes of delivery and submitted artifacts. The students also submitted a group project file which documented the group’s findings and details of the inquiry process. The teacher evaluated the groups based on criteria related to both the processes and the products of the project work. A copy of the assessment rubric (Table 1) is included in the appendix. Assessment of the PBL project constituted 10% of the marks for the school term. Knowing that the project counted toward their final grade encouraged most of the students to put in their best effort.

At the end of the project, the students self-evaluated themselves on their knowledge application, communication, and independent learning skills by reflecting and completing a “How did I Do?” form. The students also responded to a feedback questionnaire where they reported on the problems they faced when working on their projects in a PBL context.

Data Collection and Analysis

Planning forms and reflection logs were used to facilitate student knowledge construction, capture students’ thinking processes, and to record their progress. Together with students’ project files, these documents also served as data sources for subsequent analysis. The students were observed during project work sessions and field notes were taken.

All groups were audiotaped or videotaped, in turn, during selected in-class interactive discussions and hands-on activities. The students' taped discourse during these class activities was transcribed using a mixture of verbatim transcription, paraphrasing, and narrative description of the content. Group leaders from the nine groups were also interviewed twice during the study to find out their experiences of working on their projects in a PBL context. Interview questions included "What are some problems that you have encountered?," "How do you find this PBL approach?," and "What have you learned?." The interviews were audiotaped and transcribed. The teacher also found out how all the other group members were responding to and progressing in their project work through informal conversations carried out with them throughout the project.

We both conducted the data analysis which was guided by the research questions. The unit of analysis was the group for examining students' approaches to working on ill-structured problems. The focus was on group processes and products. Our analysis does not attempt to make claims about what or how individual students learned. Multiple sources of data from students' written work, oral presentations, classroom observations and field notes, transcripts from audiotapes and videotapes of group interactions, and audiotaped interviews with the students were analyzed in relation to each other. This served to triangulate the data and to help enhance the credibility of the findings and assertions made (Lincoln & Guba, 1985; Stake, 1995). For example, segments of interview transcripts that corresponded to relevant sections on the students' written work or interactions recorded on tape were checked for congruence. Observation field notes provided a context for the interpretation of data.

All relevant data from students' written work, oral presentations, group discourse transcripts, interviews, classroom observations, and field notes were analyzed jointly using an iterative process. They were first scrutinized to study the evolution and progress of students' thinking, behaviors, actions, and products during the course of the project work. The transcripts, documents, and field notes were first read through several times to get a sense of the data. Coding categories (Bogdan & Biklen, 1992) that pertained to the way students approached and worked through the problems, as well as issues and problems relating to the use of ill-structured problems were then developed to organize the data. Annotated, interpretive comments were made in the margins of the text. Illustrative instances were noted. These inductively derived categories that emerged became the tentative codes, and subsequent text segments were then annotated with the appropriate code. In constructing these categories, it was important that they could be operationalized and substantiated in the context of the data.

A constant comparative method (Glaser & Strauss, 1967) was used to cluster the codes into progressively more inclusive categories forming working hypotheses. During this forward-and-backward testing process, the codes were refined by analyzing further text segments and by adding to, deleting from, or modifying the existing list. Any regularities and recurring patterns were noted. Assertions were then made based on these patterns which were grounded in the data (Erickson, 1986), and these are substantiated and illustrated with examples. Working back and forth among the data from the various sources helped detect relationships among the categories and refine the working hypotheses on the basis of confirming and disconfirming evidence (Lincoln & Guba, 1985).

RESULTS

The findings on how the ill-structured nature of a problem influenced the way students approached and worked through the problems are presented as four assertions below, and supported with illustrative examples. They pertain to identifying problems for investigations, the importance of self-generated questions, crossing borders beyond school science, and multiple approaches to inquiry.

Identifying Problems for Investigations

Assertion 1: *When students were not given a well-defined problem to work on, several initially experienced difficulties in identifying a problem themselves. However, given the time and opportunities for discussion with family members and friends, they were subsequently able to formulate personally meaningful problems which they found motivational.*

During the problem-identification phase, 16 of the 39 students were able to quickly write down several questions pertaining to their problems of interest. The remaining 23 students initially had difficulties in generating questions and formulating their own problems. Some of these students merely stared blankly at their problem logs. Some doodled on the problem logs and seemed to be engaged in unrelated thoughts. Others were uninterested in the task, preferring to talk with their friends about other matters. Some groups also encountered problems in agreeing on what topic and problem to select for their project. Group members had to negotiate their individual interests, compromise on differences in ideas, and learn how to work collaboratively and cooperatively as a team.

Some students showed resistance to the problem-first approach in PBL, preferring to have traditional “normal classroom lessons” instead, where the teacher taught the content of the chapter on nutrition first before giving them a well-defined project to do. Such students were uncomfortable with the move from teacher-centered lessons and felt that project work of this nature was “a waste of time and effort.” A frequent response given by the students for their initial struggles in identifying a problem was that they “don’t know how” to think of problems.

However, when the students brought their problem logs home subsequently and used the time during the week to generate questions, they returned with several interesting ideas and longer lists of questions. Some students even attempted to suggest answers to their peers’ questions. The students revealed during the interviews that interactive discussions with their family members or friends also helped to generate ideas. During this process, the students discovered problems set in real-life situations which were embedded in personal contexts. For example, a student mentioned during the interview that her initially blank problem log progressively evolved into a long list of questions because she had become more aware of the nutritional issues related to her daily life during the course of the week. She read the local newspapers daily with greater interest, and paid special attention to articles on nutrition. She even asked her family members if they had any problems or questions about nutrition that perturbed them. This saw the transformation of a disinterested student into one who was motivated by problems and who would continue to search for answers. Having to seek answers to the students’ own questions set the stage for learning.

The requirement of having to write their individual questions provided students with an opportunity to revisit past experiences. This process activated their latent puzzlement and curiosity about various issues which some of them had dismissed on earlier occasions. This was the first step which led students to pursue their subsequent inquiry. After brainstorming questions individually and negotiating among themselves, the students decided on a group topic in which to frame their problems, generally one that most of them could identify with and were interested in pursuing. The problem that finally became an object of study for the students was the result of a constructive interplay between the students’ prior experiences, personal dilemmas, curiosity about a phenomenon or issue, input from others outside school, and social negotiation among group members. The project topics for the nine groups were (1) nutrition and hair growth, (2) eating disorders, (3) betel nut, (4) nutrition and color-blindness, (5) the effects of viagra on impotence, (6) nutritional value of insects, (7) ginseng, (8) slimming centers, and (9) dentition.

Despite encountering difficulties with identifying a problem, the majority of students liked the idea of generating their own topics for investigation as they could work on something that they were interested in. Furthermore, they could research on topics beyond those covered in the syllabus for their national (GCE "O" level) examinations. Several students expressed a liking for the ill-structured nature of their problems. A student indicated that she enjoyed the freedom to "come up with our own questions and answers" and found the process of inquiry fun. She also noted that "we never knew where the research would lead to and what our next steps were." Other students liked "having to learn new things on our own" and "learning things outside the classroom."

The Importance of Self-Generated Questions

Assertion 2: *The ill-structured nature of the problem stimulated students to pose questions which charted their subsequent courses of action, leading to independent inquiry.*

After the students had framed their problem in the context of their project topic, they began asking questions that directed them in their inquiry. The Need-to-Know guiding worksheet provided a framework for the group discussions. In the absence of a well-defined structure and clear parameters that set boundaries on the problem to be investigated, students were compelled to generate questions themselves that guided their learning pathways. That is, what students learned and how they learned this information were very much driven by the types of questions asked.

An example using group 7 is given below as illustration. Four kinds of questions, namely information gathering, bridging, extension, and reflective questions (Chin and Chia, 2004a), served to scaffold students' thinking and advance their knowledge in a productive manner. These questions elicited students' use of cognitive processes (e.g., comparing, explaining, applying, and reflecting) which directed them to seek the appropriate answers. The students worked on "ginseng" (a herb commonly used by East Asians) and took on the roles of nutritionists. Their problem read:

> Jiahe's grandmother has been taking ginseng regularly and insists that the family follow the good habit. Jiahe is curious about the effectiveness of ginseng. His mother decides to employ us, nutritionists, to research on ginseng.

As we can see, the above problem is ill defined without any specific questions to be answered or any prescribed directions to be followed. Other than the reference to "the effectiveness of ginseng," the problem does not allude to any other aspect of ginseng that students might investigate. Thus, there was much leeway in what students could work on, in terms of areas that they were interested in.

Having had their family members prepare ginseng tea as a health tonic for them during the examination periods, the students wanted to learn several things about ginseng. They began their search by asking questions such as "What is the plant that produces the ginseng root?" The information they found about the different species of ginseng led them to ask further questions such as "What are the different types of ginseng and their benefits?" They were curious to find out more about the ginseng plant, and to compare the differences between North American and Korean ginseng, as well as the differences between wild and cultivated ginseng. This led them to research into and learn about plant growth and nutrition, the characteristics of each type of ginseng, and how growing ginseng would deplete much minerals from the soil.

Knowing that ginseng was believed to promote the mental and physical health of an individual led them to ask "What are the contents of ginseng that make it so nutritious?" Students found out that there were several chemicals (ginsenosides) which have been identified as active ingredients of the ginseng plant. Such information-gathering questions arose directly from students' prior knowledge and were aimed at filling in knowledge gaps pertaining to factual information or basic understanding of the topic in question.

After finding out the answers to these questions, the students then asked bridging questions such as "How does ginseng affect the body systems?" which sought to link their understanding of previously learned concepts to their newly acquired knowledge, and to explain the effects of ginseng on the body. Subsequently, they found out that ginseng is believed to exert its effects in multiple ways through the digestive, central nervous, circulatory, immune, and even reproductive systems. Upon learning about the metabolism of different classes of food in the body, they also tried to trace the digestion of ginseng by asking "What processes are involved in the digestion of ginseng in the human body?" Asking such a question helped them to see the relationship between food types and digestion, apply their knowledge of digestive processes, and made learning more relevant.

Extension questions led students to think about and discover information beyond the initial (although fuzzy) boundaries set by the problem. For example, the students wanted to know "What are the different ways of cooking ginseng?" and made ginseng drinks for their classmates. They learned that ginseng is commonly brewed and drunk as tea or soup, although it may also be consumed as raw or dried slices, or in powdered form as tablets and capsules. By asking when people would take ginseng, the students conducted a survey and found out that ginseng was consumed most frequently by senior citizens for health reasons, by working adults to relieve stress, and by students during examination periods. Prompted by the common belief that the older the ginseng root, the more "nourishing" it would be, the group asked the question "How do people determine the age of the ginseng?" After checking several information sources, they then tried to apply their knowledge by counting the number of bud scale scars on the root and then estimating the ages of different ginseng samples that they had collected.

To find out the answers to their questions, the students not only referred to books and the Internet, but also visited Chinese medical halls, spoke to Chinese physicians and family members of the older generation who were more knowledgeable about traditional herbs, carried out food tests (for starch, reducing sugars, proteins, and fats) on ginseng, interviewed people who took ginseng regularly, and conducted a survey.

Reflective questions helped students to think more critically about their ideas and also to form more informed opinions and decisions. For example, after having found out much information about the purported benefits of consuming ginseng (such as relieving lethargy and increasing one's vitality), the students also wondered "Are any side effects associated with taking too much ginseng?" Upon reflecting on the problems they had faced in carrying out their project, they also realized that they had not managed their time efficiently and wisely, and reconsidered how they would do things differently if they had to carry out a similar project in the future.

Thus, by posing questions themselves, students stimulated each other in their groups to contribute content knowledge, make comparisons, propose explanations, apply learned concepts, formulate further questions, critically reflect on their findings, and to self-evaluate their performance and time management.

Crossing Borders Beyond School Science

Assertion 3: *The ill-structured nature of the problems led students to investigate multidisciplinary elements beyond the boundaries of typical school science.*

The ill-structured nature of the problems compelled the students to approach their investigations from a broad perspective, consider multiple and varied stances to the problem, and ask a variety of questions since there was no fixed way of approaching the problem. This led the students to cross the boundaries typically encountered in school science, tread into novel areas that were usually unrelated to science, and discover new realms of knowledge. Thus, there was a multidisciplinary element to students' work that incorporated international cultures, history, geography, social studies, and even art and design when they had to design creative products for their multimedia presentation. When asked how her group stumbled upon other information beyond what they had set out to seek, one student replied that "We just kept asking all the possible questions." Examples from Group 6 (nutritional value of insects) and Group 3 (betel nut) and are used to illustrate this.

Group 6, which worked on "nutritional value of insects," had read an article in the local newspapers on edible insects and were intrigued by the idea of eating insects as an alternative source of food. Their problem was

> May plans to start a new kind of business selling edible insects. Before she starts, she will have to find the suitable kinds of insects and to make sure that the insects are nontoxic. She will also need to know if her products will sell well. In order to promote the sales, she will have to know the nutritional/medicinal value of the insects. As salespersons of the shop, we are given the tasks to research on our products.

In having to role-play a character in the problem statement with whom they could identify, students felt a sense of ownership of the problem. They enjoyed what they perceived as a "game of make-believe," and went to great lengths in pursuing their areas of interest. As sales persons who were interested in and considering the feasibility of starting a new kind of business promoting sales of edible insects, they wanted to find out why some people ate insects, what were the different methods of cooking insects, and the nutritional and medicinal value of insects. Their questions included "Why do some people eat insects?," "What is the taste of insects?," "What are the benefits and harms of eating insects?," and "When we are on the verge of starvation, can we eat insects to survive?" These questions prompted the students to propose reasons for why some people eat insects, compare the pros and cons of insect consumption, and ask themselves if they would resort to eating insects as an alternative food source if they were on the brink of starvation.

Subsequently the students found answers to their questions by searching through newspaper articles, books, and the Internet, interviewing the owner of a shop that sold edible insects, and conducting a survey to find out people's reactions to eating insects. They were surprised to find out that insects were eaten as a delicacy, and were even a source of staple diet in some cultures. For example, some tribes in South Africa eat roasted termites and in the northern-eastern region of Thailand, some poor village farmers have acquired the taste for pests such as worms, weevils, locusts, and caterpillars. There are also shops in America selling chocolate-coated bees and ants. The students' findings included recipes for mealworm cookies, chocolate crickets, and ant lemonade.

The students also found out that many insects are lower in fat content and higher in protein content than beef, lamb, or chicken, and that the nutritional values of insects are equal, if not better than traditional meat choices. All of them were initially flabbergasted at the idea of eating insects and believed that most insects tasted horrible and were poisonous.

However, they read some articles which claimed that insects may not taste as bad as they had thought. Roasted grasshoppers were supposed to taste like prawn crackers, silkworms like mashed brown beans, fried locusts and crickets are crunchy and tasty when salted, and giant water beetles taste like king prawns' roe.

Encouraged by what they had found out, they asked themselves "Will we eat insects?" This led them to analyze the problem holistically, evaluate their options, make conclusions, and arrive at a decision. They shed their initial inhibitions and purchased two insect lollipops and two packets of barbequed- and cheese-flavored insect larvets (imported from California) from a shop at a local mall that sold edible insects. They tasted the insects themselves and even got some friends to try them. They also interviewed the salesperson at the shop and found out that the sales of edible insects had not been too promising because most people had a mental block against eating insects. As a solution to their problem, they recommended that although there were some reasons supporting the consumption of insects as a source of food, May (the character in their crafted problem) should not open the insect shop in light of general local public resistance to the idea. To justify making this decision, the students presented their arguments for and against May's proposed business setup.

Group 3's inspiration for studying the betel nut came from their observation that the Indian school attendant, who had the habit of chewing betel nut, had black-stained teeth. The students wondered why some people enjoyed chewing the nut, why it caused teeth to stain, and what effects it had on the mouth and the body. They also tried to figure out how one's saliva reacted with the betel nut contents, and wanted to solve the mystery of the red coloration that ensued from chewing the nut. They asked questions such as "What does betel nut contain?," "Where does it come from?," "Why do people eat it?," "How is it consumed?," and "Why do the teeth turn black?."

They searched the Internet and interviewed a person who regularly chewed the nut. They found that betel nuts come from the *Semen arecae* palms which are indigenous to the Malayan group of islands. People chew the betel nut because it is a stimulant. It is believed to be able to sweeten breath, harden gums, and improve digestive powers. The betel nut is chewed together with slaked lime wrapped in betel leaf. A reddish-violet coloration ensues when the alkaline slaked lime reacts with the tannin present in the nut. This stains teeth heavily and causes them to appear black. Excessive consumption also leads to tumors in the oral cavity.

After unraveling "the mystery behind the betel nut" (as one student put it), the students further asked "For what other purposes is betel nut used?" and acquired information that they did not originally set out to find. They uncovered the history behind some traditional rituals related to the betel nut and its symbolism in some cultural practices. For instance, the group found that the betel nut is used in remote areas of India to symbolize fertility and unity, and to embalm the dead. A student recounted that in making a field trip to "Little India" (a region in Singapore where there is a concentration of shops selling Indian foods and merchandise) to buy the betel nut for their investigations: "The old man [stall owner] told us that they even use betel nut in exorcism!" The group had originally believed that the betel nut was chewed only by the Indians, based on their observation of some older members of this ethnic community in Singapore. However, they later found out that the betel nut chewing habit is also popular with the Chinese in Taiwan and some parts of China.

In gaining knowledge beyond the topic of nutrition, a member of the group commented, "We were not just learning biology. We now understand why the Indians in Singapore chew betel nut and I can use what I learned in my National Education project on social and religious harmony." In being able to transfer the knowledge she had acquired across disciplines, this student's learning outcomes were enhanced.

Multiple Approaches to Inquiry

Assertion 4: *Having students think about how they could find out what they wanted to know led them to interesting and creative information-gathering and data-collection procedures and to pursue different types of inquiry.*

One of the guiding questions in the students' Need-to-Know worksheets asked "How can you find out what you need to know?" Instead of the teacher telling students what they should do to find the answers to their questions, the students had to consider multiple methods and decide for themselves. They had to figure out which of the available alternative methodologies were appropriate, instead of simply following given instructions on what to do. This gave rise to different modes of inquiry that went beyond the traditional hypothesis testing or experimental paradigm that is common in school science. For example, besides obtaining information from traditional sources such as library books and other printed materials, the students also surfed the Internet, conducted both paper and electronic surveys, field studies, interviews, as well as carried out laboratory investigations. This broadened their knowledge of the different possible methods that researchers use in scientific inquiry.

Seven out of nine groups conducted surveys. Most of the groups gave out questionnaires to friends and classmates. When data across age groups were required, they approached relatives and family members for help. For example, Group 6 wanted to collect information on people's opinion of eating insects instead of meat, as an alternative source of protein. They used e-mail and forwarded their questionnaires to friends and strangers. They also used the Internet relay chat (IRC) as a platform for their surveys. Group 8 also conducted a survey to find out what were the most popular methods of slimming.

The students also conducted field studies and interviewed relevant people. For example, Group 1 sought answers to questions about whether bad diet, polluted air, heat, and dyeing caused hair loss, and what were some possible remedies. They visited a hair treatment salon, consulted the doctor via "e-circle," and interviewed both hairdressers as well as people who suffered from severe hair loss problems. In the process, they learned that hair loss was often attributed to factors such as heredity, aging, hormonal changes, illness, extensive hair treatments, stress, and radiation therapy. Group 9, which did their project on "dentition," took on the role of dental health personnel who wanted to educate people about dental diseases. Their investigations led them to visit a dental fair where they found out answers to their questions on the causes and processes involved in tooth decay.

Five groups designed and performed laboratory experiments in search of answers to their questions. Students from Group 1 hypothesized that human hair, comprising mainly protein, might constitute an additional source of nitrogen to soil for the growth of plants. They set out to investigate this by studying the growth of a balsam plant after they added human hair to the soil, and then compared its growth with a control plant. The students from Groups 1, 3, 6, and 7 also applied what they had learned about food tests to test for the presence of starch, reducing sugars, protein, and fats in human hair, betel nut, insects (mealworms), and ginseng. Group 9 students set up an experiment with a control to investigate the effects of fluoride on chicken bones and egg shells as they wanted to test whether fluoride would strengthen them.

Wherever possible, the teacher integrated students' ideas and project findings into her lessons. For example, during the lesson on food tests, Groups 1, 3, 6, and 7 which carried out these tests, reported their findings to the class. Group 2, which investigated the topic on eating disorders such as anorexia and bulimia, shared the concept of a balanced diet and diseases related to malnutrition. Group 8, which worked on slimming centers, introduced to the class the composition and storage of fat in the body, as well as the causes of obesity and its relation to heart disease. Group 9 reported on the structure of human teeth, the role of teeth in the mechanical digestion of food, the dietary importance of calcium in the formation of strong bones and teeth, how bad nutrition can cause cavities to develop, and issues regarding wisdom teeth.

DISCUSSION

In this section, we discuss issues and challenges associated with the use of ill-structured problems, as well as implications for instruction based on the findings of this study. These pertain to (a) identifying a problem for investigation, (b) asking questions to negotiate the learning pathway, (c) deciding what areas and questions to pursue and focus on, given a multitude of possibilities, (d) figuring out how to extract relevant information from the available mass and synthesize answers to the questions posed, (e) using PBL in school settings in the face of time constraints, and (f) the teacher having to wear many hats as a metacognitive guide. We raise questions pertinent to these problematic issues, and then propose some solutions. We also offer some suggestions for the management and implementation of PBL that uses ill-structured problems. In addition, we discuss the factors facilitating the implementation of problem-based project work in this study.

Issues and Challenges Associated with the Use of Ill-Structured Problems

Issue 1: Identifying a Problem for Investigation. The students were confronted with a less familiar task of having to identify and define a problem for investigation themselves, having been accustomed to problems given to them by teachers. Some students initially faced difficulties in formulating a problem and struggled hard to brainstorm ideas. They were probably not used to thinking hard and deeply on their own about problematic issues, and were reluctant to try.

How, then, can teachers help students to identify a problem for investigation? Giving students time to think outside class can help them in the problem-identification process. Students can also be encouraged to include friends and family members in their search during the problem-identification phase in PBL as this makes learning more interesting for them. This is particularly when a large proportion of students' inspirations for their ideas may come from the home and through interaction with significant others, rather than from formal lessons at school (Chin and Chia, 2004a). When learning is related to real-life situations, students' motivation increase as they own these problems, dilemmas, and their resolutions.

Some students need a "seed" idea to activate latent memories of a past experience or a memorable event. Seed ideas can arise from a teacher's question or demonstration of an activity. In this study, the teacher also used nine articles on issues related to nutrition to sow these seed ideas. Subsequently, these ideas led to a good list of questions during the problem-identification process. The teacher can help students by asking appropriate guiding questions to plant these seed ideas, which can then prime a series of questions related to the topic of interest. The teacher can also form "idea circles" where students are grouped together to generate questions and ideas on topics of interest during the problem-identification phase.

Issue 2. Asking Questions to Negotiate the Learning Pathway. The problems that students worked on in this study were not encapsulated in a clear or focused investigative question at the outset. Given this situation, student-generated questions played a vital role in steering the direction of students' inquiry. They influenced the nature of students' thinking, their subsequent pursuits and the answers obtained, and consequently, the type and extent of knowledge gained. Students' questions helped to scaffold students' thinking probably because they elicited thoughtful responses such as explanations and inferences, and helped to construct cogent arguments.

Questions can also serve as cues to direct students' attention to important information that they might overlook. They can stimulate students to brainstorm different ideas, make comparisons, weigh pros and cons of various solutions, evaluate evidence, construct arguments, and provide justifications. This suggests that in the absence of any well-defined structure and procedures to guide one's learning, the ability to pose questions and seek answers is a useful learning tool. Teachers should encourage students to raise their own questions, and provide scaffolding for students who have difficulty in generating their own questions.

How, then, can teachers help students to ask productive questions that can advance their thinking, and then subsequently to organize and consolidate what they have learned? The use of various graphic organizers and guide sheets such as problem logs, mind maps, Need-to-Know worksheets, and Learning Log and Project Tasks Allocation forms can help students to structure and organize their questions and ideas, making them visible to both the teacher and the students themselves. A teacher can promote thinking by having students work with such scaffolds, which provide a visual focus, and allow thoughts to be captured and consolidated. When students document their learning journeys with their questions and ideas, they become more progress driven as they watch how their knowledge of the topic increase along the way. In addition, students' responses to "What do you need to know?" in the Need-to-Know Worksheet can act as a compass, directing the inquiry and helping the students plan the next steps of action.

In most classrooms, teachers typically do not begin teaching a topic based on what students want to know. Instead, they typically adopt a "top-down" approach in teaching science concepts and decide how the content should be introduced to students. An alternative way of introducing a topic would be to use a "bottom-up" approach where instruction begins with students identifying questions related to what they would like to know about a given topic. A Question Web or Need-to-Know sheet can be used as a graphic organizer for this purpose. In this way, students would make their questions explicit and the teacher can then follow up on these questions by situating the teaching in the context of these questions raised. Further suggestions on how teachers can encourage students to pose questions are given elsewhere (e.g., Chin, 2004; Chin, Brown, & Bruce, 2002).

Issue 3: Deciding What Areas and Questions to Pursue and Focus on, Given a Multitude of Possibilities. Because of the ill-structured nature of the problem, students had a variety of options in deciding what areas to pursue for investigation. They had to make decisions regarding what questions were significant and worthwhile to answer. There is value in students being given the latitude to pursue whatever interests them. However, while there is richness in diversity regarding the spectrum of topics that students can investigate, the choice of specific areas of study is not simply a matter of "anything goes." What criteria can we use to determine the areas that are considered worthwhile for students to pursue?

As a general guide, the topics that students choose to pursue should be aligned to the general objectives of the lesson and have some connections to the underlying conceptual content that the teacher is hoping to foster. They should also be able to sustain students' interests, and the content involved should not be trivial, distasteful, or objectionable. Also, "good" questions to pursue are those that lend themselves to empirical investigation, and lead to gathering and using data to develop explanations for scientific phenomena. They should also be sufficiently robust and fruitful to stimulate related questions to drive the inquiry. The procedures that students use to answer their questions must be accessible and manageable, and appropriate to their developmental level.

Furthermore, because students can take multiple valid paths of action in deciding how to deal with a problem, teachers may encounter a remarkable range of ideas and artifacts in their finished products, all of which may be considered viable. This is because what students learn from their project work is determined by how they act upon the available resources in their environment. Thus, teachers may have to shift to a different conception of what counts as a successful or adequate product (Kass & MacDonald, 1999).

Issue 4: Figuring Out How to Extract Relevant Information From the Available Mass and Synthesize Answers to the Questions Posed. The ill-structured nature of the problem allowed students to utilize different data sources and methods of inquiry to seek answers to their variety of questions. Also, with the availability of the World Wide Web and search engines on the Internet, most students preferred to search for information via the Internet instead of going to the library. This was because of the convenience and the ease in obtaining information from the Web sites. However, undiscerning students may use copy-and-paste strategies and end up in a wholesale transfer of information from the Web site onto their presentation reports without much critical analysis or synthesis of the available materials.

While there is value in the serendipity of discovering information that one does not set out to seek, the huge amounts of irrelevant information collected during searches also overwhelmed students and occasionally distracted them from focusing on the issues directly related to their problems of concern. When students found little information relevant to their posed questions, they tended to indiscriminately include all other information into their projects. The issue here, then, is: How can teachers guide students to think critically about the overwhelming mass of information that confronts them, and to distill those aspects that are relevant to their learning objectives?

Students must be taught how to assess the credibility of the source, evaluate the validity, reliability, and accuracy of the information they obtain from the Internet, discriminate between relevant and irrelevant information, and synthesize the information from various data sources. This is particularly the case for answers to ill-structured problems where students need to analyze, evaluate, organize, and tailor the extracted information to respond to the specific questions posed. The teacher has to point out to students why the copy-and-paste strategy is inappropriate. Students should also be taught that all information gathered should be acknowledged as well as how to cite references properly. Teachers must also help students to integrate what they have learned with the key concepts relevant to the curriculum.

Issue 5: Using PBL in School Settings in the Face of Time Constraints. In PBL, students may venture into areas not covered in the mandated school curriculum. They may also have to explore a fair bit before they have a clear sense of what they are going to do, modify and reorganize their plans, or abandon some ideas in light of new developments. Thus, particularly in school systems which have standardized tests, many teachers may view PBL activities as a luxury that they cannot afford, given their time limitations. They may be afraid that their students would be disadvantaged as precious time may be wasted. How, then, can teachers implement PBL activities that focus on standard curriculum objectives and that would enable students to acquire the requisite content knowledge?

In such contexts, teachers may not be able to give students as much leeway in pursuing their own areas of interest because students may stray too far away from the central objectives of the lesson and become distracted by topics that are peripheral to the core content. They could then use problem-based project work for enrichment instead, or as "post-holes" which are shorter problems that teachers can occasionally infuse into the regular curriculum (Stepien & Gallagher, 1993). Teachers would then need to nudge students toward working on areas that are more narrowly focused and that are not overly beyond the confines of the syllabus, and to make sure that students do not deviate too much from the intended objectives of the lessons.

A key element to consider is the intended learning outcomes—the particular science concepts the teacher wants students to learn, the skills to be acquired, and the understandings about the nature of scientific inquiry. The teacher could write down the specific curriculum and content objectives and then check off those that are relevant to the problem. If the objectives are not met, then the problem needs to be revised so that there is a closer match. This will ensure that as many objectives as possible are addressed.

When different student groups investigate selected areas in depth, this would lead to a situation where each group would have "specialized" knowledge of a certain area, while knowing little about other areas. To address this problem and ensure that all students have access to a common pool of consolidated information in the time available, individual groups that work on specialized topics could exchange and share their knowledge with other groups, through class presentations, compiled notes, or cooperative learning strategies such as *Jigsaw* (Aronson et al., 1978).

What gains might be there be for students who engage in PBL activities? Although the teacher may cover less content through PBL instructional activities, this can be offset by other gains such as increased motivation in students, extra general knowledge beyond the curriculum content, as well as the acquisition of critical and creative thinking and problem-solving skills. In addition, students also experience first hand, the nature of authentic inquiry and the different methods of finding answers to their questions.

In this study, the multidisciplinary flavor of such a project allowed students who were disinclined toward science or whose interests lay outside science, to become more motivated as they were able to integrate their other interests with science, thus making the subject come more alive for them. Students were intrigued by real-life issues embedded in social contexts, especially those that had a direct impact on their lives. They generated a wide range of related topics of personal relevance that added a dimension of richness to their learning. These topics had science–technology–environment–society connections and impinged on issues which teachers do not normally discuss in regular lessons. This "extraneous" content knowledge that students acquired was considered worthwhile as it increased students' breadth of knowledge in related areas.

Teachers in Singapore are often encouraged to infuse a multidisciplinary element into their science lessons, especially in project work, to help students see how science can be linked to other subjects. At times, they experience difficulty in doing this and have to think hard in coming up with ideas on how to integrate their science lessons with other subjects to make it multidisciplinary. This is because traditionally, science has always been taught as a unidisciplinary subject. However, in PBL, this multidisciplinary element arises naturally as it is embedded in the ill-structured nature of the problem. Thus, PBL is inherently suited to situations where a multidisciplinary approach to learning is valued or desired.

More important, in the course of acquiring this extraneous knowledge, students had to engage in valued process skills such as gathering information, determining if additional information is necessary, suggesting alternative solutions, generating hypotheses and explanations, making comparisons, as well as classifying, analyzing, evaluating, and synthesizing this assorted information into a coherent product. Students were also stimulated to think more critically and question the validity of some traditional beliefs and folklore in the light of scientific evidence. Consequently, they learned to be more discerning in their evaluation of traditional myths and practices. For example, researching into the betel nut led Group 3 students to debunk certain beliefs and to demystify their ideas about the nut.

Because students in this study were encouraged to develop their own approaches to seek answers to their questions, they learned that inquiry could take several different forms. This made them aware that answers to various questions could be obtained via different appropriate and valid methods, and that there is no one scientific method. In view of this, one pedagogical implication is that teachers would need to teach their students the rudiments of other common methods of inquiry, data-collection, and data analyses beyond the laboratory experiment, such as how to draw an appropriate sample for surveys and interviews, basic statistics, and the use of graphs and spreadsheets.

In having to work with ill-structured problems, the students learned to "exploit the associated interpretive flexibility of the problems" (Roth & McGinn, 1997), deal with the complexities and messiness of everyday life problem solving, and to bridge the gap between in-school curriculum and out-of-school experiences. Engaging students in ill-structured problem tasks can help them see the meaningfulness and relevance of what they learn and facilitate transfer by contextualizing knowledge in authentic situations. That is, the students learn to connect their academic, personal, and social lives. The example of the student from Group 3 who developed a deeper appreciation of other cultures and who was able to apply what she had learned about the betel nut to her National Education project is a case in point.

Issue 6: The Teacher Having to Wear Many Hats as a Metacognitive Guide. Teaching science via PBL demands a diverse range of teacher roles beyond that of "teacher-as-knowledge transmitter." What then, does it mean for a teacher to be a "facilitator" or "metacognitive guide"? In her model of "collaborative inquiry," Crawford (2000) discussed a myriad of roles for the teacher. These roles include a motivator, diagnostician, guide, innovator, experimenter, researcher, modeler, mentor, collaborator, and learner. They apply equally well to a PBL approach to teaching science. We suggest the additional roles of a provocateur and facilitator of opportunities.

The teacher needs to encourage students to take responsibility for their own learning and to provide cognitive, social, and moral support so that they would persist in working on their problems. She has to experiment with and research into innovative ways of teaching that guide students to use the valued cognitive processes, evaluate her own teaching, and be open to learning new strategies and concepts. She also has to model the attitudes and attributes of scientists, as well as relinquish her role as director of instruction and instead co-inquire with students on areas that she may be unfamiliar with. In addition to these, the teacher also has to challenge students to question their own assumptions and reconsider their original ideas or points of view, where necessary, as well as provide the necessary conditions to maximize students' use of conceptual, social, and material resources.

The teacher can leverage on the funds of knowledge of his or her students' world outside the context of the classroom, and tap into the "hidden" home and community resources of the students. Once mobilized for learning, these can become a useful social, cultural, and cognitive resource for classroom instruction.

In using the various forms of scaffolding mentioned earlier (e.g., "seed" idea, guiding questions, various graphic organizers, and guide sheets), the teacher has to decide on what would be an optimal level of guidance. This would depend on the students' prior experience with PBL, as well as their background knowledge, ability, and motivational levels. Too much guidance will turn an ill-structured problem into a structured one, while too little guidance will leave some students floundering.

Factors Facilitating the Implementation of Project Work

Implementing problem-based project work in this study was challenging in the context of a large class size, 40-min class periods, pressures of national examinations, and the emphasis on students' individual grades. Despite these constraints, there were several local factors that facilitated its implementation. First, in its efforts to encourage independent learning in students, the Ministry of Education has made project work a compulsory part of the school curriculum and also a criterion for university entry. It has provided much funding and resources. These include providing project work resource packages and extensive information technology support to schools, as well as training on project work for teachers. Thus, project work is now an integral part of the school curriculum. Second, the science laboratories in this school, as in most other schools in Singapore, were well equipped with laboratory technicians who ensured that the teacher and students were able to conduct practical work efficiently. Third, the assessment items on the national examinations have gradually incorporated more "thinking" questions so there has been more incentive for teachers to engage in inquiry-based instructional practices. Fourth, the teacher involved in this study was progressive in her outlook and subscribed to a constructivist philosophy of an activity-oriented curriculum.

Conclusion

From the above discussion, we see that the use of ill-structured problems in PBL can engage students in ways that elicit desirable cognitive processes which are good habits of mind. These cognitive processes include formulating a research problem, posing questions, designing and conducting investigations, making comparisons, proposing explanations, applying prior knowledge to new situations, generating alternatives, constructing arguments with justifications, making decisions, and monitoring the progress of one's work. Good habits of mind include brainstorming to identify problems for investigation, generating questions to direct their own learning, considering multiple and varied stances to a problem, figuring out how to solve a problem via different types of inquiry, and thinking independently. Because students make their own decisions about what directions to take in their investigations, what information to collect, and how to analyze and evaluate this information, PBL can accommodate a variety of learning styles as there may be alternative ways of reaching a solution to a problem. The problem can promote a range of activities that allow students of different levels to contribute to the solution (Delisle, 1997). Problem-based learning, which embodies values such as self-directed learning, active engagement, generativity, multiplicity of ideas, reflectivity, personal relevance, and collaboration, is one of the best exemplars of a constructivist-learning environment.

Most of the authentic problems in our lives are ill structured. Given this state of affairs, if students are given the experience of working on ill-structured problems in school science, they would be better prepared and equipped to face real-world challenges in their future.

APPENDIX

TABLE 1
Assessment Rubric Used for the Project Work

Standards for Excellent Work

Your teacher will be judging you on the following:

1. Your Process	Evidence	Marks
Your sources of inspiration for the problem.	Project theme and interview	/ 5
Problem is real and relevant to the theme of "Nutrition".	Group Problem Statement	/ 5
Your group generates a variety of ideas and gives convincing reasons for deciding on the problem.	Individual *My Problem Log*	/ 10
Problem solving tasks are well defined and good thinking questions are asked.	*Need-to-Know* worksheets Project planner	/ 5

2. Your Product	Evidence	Marks
Your group shows that you have made thorough use of knowledge from the content of the theme "Nutrition".	Explanatory report	/ 5
Your group has carried out some experiments / data-collection procedures in the course of your Project.	Explanatory report	/ 15
Your group findings were well-analyzed, interpreted and reported.	Conferences / Explanatory report	/10
Your explanatory brief is clear and comprehensive and explains well all of the steps that you have taken to solve the problem.	Explanatory report	/ 5
There is a high level of creativity in your ideas, approaches, solutions, and use of resources.	Explanatory brief	/ 10

3. Your Oral Presentation	Evidence	Marks
The group presentation is very well organized as a whole.	Oral presentation	/ 5
Ideas and findings were well communicated.	Oral presentation	/ 5
IT/visual aids used are effective.	Oral presentation	/ 10
The group was able to answer the questions raised by the audience well.	Oral presentation	/ 10

Total Score: **/100**

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