Chapter 9
From Problem-Based Learning to Knowledge Creation

Jennifer Yeo

Introduction

The fast-growing body of scientific knowledge, the rapid advancement of science and technology, and the influence of science and technology in our daily life have shifted the goals of K-12 science education from one that is focused on content acquisition to one that emphasizes creative and meaningful use of scientific knowledge. Problem-based learning (PBL), with its activity centered on problem solving through investigation, explanation, and resolution, is highly regarded as an effective inquiry model to bring about this integration of new knowledge in the context of its use (Greenwald 2000; Hmelo-Silver 2004; Sonmez and Lee 2003). Its emphases on student centeredness and collaborative learning were also aligned with the theories of constructivism regarded to be necessary conditions for developing deep understanding of disciplinary content knowledge (Savery 2006).

Yet, the implementation of PBL in high school learning was fraught with difficulties. One of the problems is the disparity between the nature of PBL and K-12 educational settings. First, their goals are different. While PBL aspires for lifelong skills, K-12 educational settings covet curriculum coverage and excellence in high-stakes examination (Hmelo-Silver 2004; Savery 2006). Thus, PBL's student-centered approach and strong focus on process skills may not be considered a superior approach to the tried-and-tested methods of "teaching to the test." Second, the highly structured classroom organization of K-12 schools and the compartmentalized subjects in the school curriculum would present a hurdle in accommodating the flexibility in time and subject organization needed in the implementation of a more fluid and multidisciplinary nature of PBL.

Besides the mentioned problems, another systemic problem, and perhaps a more significant one, would perhaps be the tension between the emphasis on content

J. Yeo (✉)
National Institute of Education, Nanyang Technological University, 1 Nanyang Walk, Singapore, Singapore
e-mail: jennifer.yeo@nie.edu.sg

S.C. Tan et al. (eds.), *Knowledge Creation in Education*, Education Innovation Series,
DOI 10.1007/978-981-287-047-6_9, © Springer Science+Business Media Singapore 2014

learning in K-12 science classrooms and the focus on the development of skills in PBL. For example, science teachers in Angeli's (2002) and Lee and Bae's (2008) study experienced pressure to cover the contents specified in the official syllabi in their implementation of PBL. Furthermore, the meta-analyses of the effectiveness of PBL for content mastery in school setting such as those conducted by Albanese and Mitchell (1993), Vernon and Blake (1993), and Hmelo-Silver (2004) were found to be inconclusive. A meta-analysis by Douchy et al. (2003) on the effect of PBL on knowledge and skills in higher education and high school in general showed a positive effect on the skills of students, but a similar conclusion could not be made about the content knowledge acquired. While there were a few studies that produced evidence of an increase in achievement in content knowledge (e.g., Liu et al. 2006), there were those that showed no significant difference in content acquisition between students schooled in PBL and the traditional approach (e.g., Gallagher and Stepien 1996; Mergendoller et al. 2000).

This study was undertaken in an attempt to address the anticipated problems with systemic factors faced by schools implementing PBL and uncertainty of its effectiveness in bringing about both content mastery and process development. The goal was to look into the implementation of PBL in a local high school and to identify the tensions that arose so that interventions can be introduced to achieve the goals of science education in Singapore. The aim of this study was thus to simultaneously test the theories of PBL that informed the interventions as well as improving the practice of PBL. The dual emphasis on theory and practice in this study justifies the use of design research as the intervention methodology in this study, in which learning is studied in context through systematic design and study of instructional strategies and tools (Brown 1992). This study was conducted in three different science classrooms, one for each research cycle, set in the natural setting of the participating school. It involved the active participation of the teachers teaching the classes in the theory-building process and practice refinement in each research cycle.

In the following sections, this chapter describes the transformation of PBL in a local high school through design research as it sought to implement PBL to foster deep science learning and problem-solving skills.

School Science Learning and PBL

What School Science Learning Entails

This study takes the view that science learning is a meaning-making process (Mortimer and Scott 2003). As the body of scientific knowledge is defined by the unique language it uses to make sense and to communicate its interpretation of the world, students learning science need to appropriate the ways in which different forms of language are used to construct meaning scientifically. In other words, students should be engaged in making sense of the meanings inscribed in different forms of languages, using them to communicate with one another meaningfully and producing creative solutions with them (Bereiter et al. 1997).

Drawing from the theories of situated learning (Lave and Wenger 1991), embodiment and social development of learning, students' meaning making of science should be supported by an environment that provides (1) an authentic context for students to participate in the meaning-making practices of science, (2) relevant experiences of similar phenomenon for uncovering the meaning inscribed in the language of science, and (3) a platform for interaction whereby students learn through a collaborative process. An authentic context in which the system of scientific knowledge is constructed allows connection between the real world and the abstract language of science to be made effectively. The coupling of our felt experiences with meaning in theory of embodiment (Varela et al. 1991) highlights the importance of engaging students in similar kinds of phenomena through which particular meaning patterns have been made. The inherent meaning in interaction (Vygotsky 1978) suggests science learning as a collaborative process of knowledge construction whereby students use a language to communicate with one another and to make sense of one another, thus helping them develop a meaningful and coherent understanding of the world.

How PBL Supports Science Learning

The conception of PBL was triggered by the realization that the traditional method of separating content from practice did not facilitate medical students' application of content to context (Savery 2006). PBL focuses on the application of newly found information in solving problems in real-life contexts (Savery and Duffy 1996; 2001). Its learning process, shaped and directed by students, is organized around investigation, explanation, and resolution, while the teacher acts as a metacognitive coach (Greenwald 2000; Hill and Smith 2005; Hmelo-Silver 2004). The features of PBL – (1) authentic problem, (2) students' active participation in the problem-solving process, and (3) collaborative and self-directed problem solving – are aligned with the conditions of school science learning described above. Table 9.1 shows the alignment between the features of PBL and conditions of school science learning.

While the features of PBL in respect to the conditions of science meaning making suggest that PBL is a suitable pedagogical approach, research findings did not seem evident. The goal of this study is hence to refine the pedagogical approach to support science meaning making more effectively. The following sections describe each of the research cycles in turn and explain how and why interventions were introduced to improve the meaning-making process in science learning.

Table 9.1 Alignment between features of PBL and conditions of school science learning

Conditions of school science learning	How PBL aligns with these conditions of school science learning
Context	Authentic problems in PBL provide a meaningful context for science learning through similar types of problems that scientists solve in their everyday practice
	Similarity between the problem-solving process of PBL (generating hypothesis, exploring possible solutions, investigating the problem, analyzing results, and generating solutions and recommendations) and the science inquiry process (hypothesis generation, hypothesis testing, and theory-building process that scientists use to construct scientific knowledge)
Experiential	The problem-solving process provides the platform for students to experience the phenomena and make use of language and other forms of representations to communicate their felt sensations and to think about the phenomenon studied
Interaction	The collaborative and self-directed nature of PBL allows students to work in small groups to construct knowledge. With the group collaboratively directing their own efforts in problem solving, they learn to own their learning and develop scientific practices such as argumentation, questioning, and reflection

Methodology

This study was a 2-year design research (Design Research Collective [DRC] 2003) aimed at refining the theory and processes of PBL for high school science learning. Three research cycles were carried out during this 2-year research project. The findings of each research cycle informed the interventions introduced to the next cycle. In each cycle, both the outcome of PBL and the process of learning (activity) were examined in order to understand how the interventions introduced supported science meaning making. The analyses focused on (a) the enactment of PBL and (b) the extent of science meaning making achieved. Using cultural-historical activity system as an analytical framework, the activity system of the enacted PBL was reconstructed for each research cycle.

The Field Site

This study, conducted in T Academy (pseudonym), was a partnership between the teachers in the school and researchers of this project to refine an instructional program that the school had embarked on. T Academy had developed the THINK cycle, a new pedagogy for science, to offer its students a broader learning experience. It was an instructional model based on the PBL approach that consisted of five stages of problem solving, namely, trigger (T), harness (H), investigation (I), network (N), and know (K). In this approach, students, working in small groups, were presented with simulated problems of the real world (T). They would identify questions that they need to investigate (H) before embarking on a series of investigations (I), which may include searching for information or conducting experimental investigation. In the process of solving the problem, they would network (N) with fellow team members and experts. Finally, they would present their solution to a panel of judges (teachers) to demonstrate their knowledge gained (K). Throughout the THINK cycle, each group was supported by a teacher facilitator who acted as a metacognitive coach. An online discussion platform was introduced in the second and third research cycles to facilitate collaboration.

The Research Cycles

Three research cycles were conducted over two academic years, one in the first and two in the second. The THINK cycles in this study were conducted with grade 9 students. In each cycle, one group of students working together on a given trigger problem was selected as the case study. The students in each case were similar in academic and cultural background as issues arising from differences in academic and cultural factors were beyond the scope of the study. Throughout the study, there was a strong partnership between researcher and three physics teachers to engineer changes in the classroom as well as to improve PBL theory based on empirical evidence. Two researchers worked with the teachers in refining the PBL process, attended almost all the lessons that the teacher conducted, and sometimes acted as a co-facilitator.

Data Collection

For each research cycle, interaction among the students was the key data for reconstructing the THINK cycle activity. Video recording was used to capture face-to-face interactions, and online interactions were recorded in the database of the online forum. Other sources of data included (a) interviews with teachers and students to understand their actions, motives, and goals and (b) the artifacts produced by the students which provided more information about their learning processes.

Analysis Method

School learning is a specific historical type of activity, with specific objects that drive classroom practices (Miettinen 1999). To make sense of the events taking place among the people and materials in the enacted PBL classrooms, *cultural-*

historical activity theory (CHAT) was adopted as a theoretical lens for analyzing the activity by connecting the activity enacted (actions and behavior of the teacher and students) to the motive that drives the enacted activity and instruments that afford the activity. It offers a three-level scheme for organizing an activity: activity, action, and operation (Engeström 1999). Activity refers to a conscious process that takes place, as opposed to the innate property of the activeness of animals and human beings (Engeström 1999; Kozulin 1986). In a science classroom, an activity refers to the classroom practice employed for science learning. What distinguishes one classroom activity from another is the motive that drives each activity and the object that the activity is oriented to. For instance, a traditional approach to science learning is often oriented toward mastery of knowledge, driven by the need to prepare students for examinations. On the other hand, PBL is oriented toward problem solving in order to prepare students to solve real-world problems (Savery 2006). An activity is translated into reality by chains of goal-directed actions. For instance, a didactic teaching approach may be made up of a series of events such as a motivational demonstration, individual seatwork, and presentation through different forms of media. Each learning event is considered a classroom action. An action, in turn, is made up of a series of operations. These operations refer to the specific behavior of students during learning events. For instance, the operations of doing a science experiment may include measurement, drawing graphs, calculating, and writing.

Expanding from this three-level framework is the expanded CHAT framework (Fig. 9.1) by Engeström (1987), who maintains that an activity is not an isolated activity system existing on its own. Instead, it is part of a larger social cultural system in which it is embedded in, including the norms of the activity (rules), community members (community), and their roles (division of labor). Thus, analysis cannot be taking place at the action level, but rather at the activity level. The expanded version of CHAT takes into consideration the influence of the social cultural context in which the classroom activity is taking place. The reconstruction of the enacted PBL thus involved identifying the cultural-historical factors influencing the classroom activity taking place.

Research Cycle 1

Participants

The first research cycle was carried out in Class 1E, with 23 (8 boys and 15 girls) high-achieving students. Prior to this research cycle, the students had completed five other THINK cycles – three on biology, one on chemistry, and one on physics – where they worked in groups of four or five. For this research cycle, a group of four students, three girls and a boy, was selected as this group was similar in their academic and cultural background. The teacher was Mr Chen, who was also the

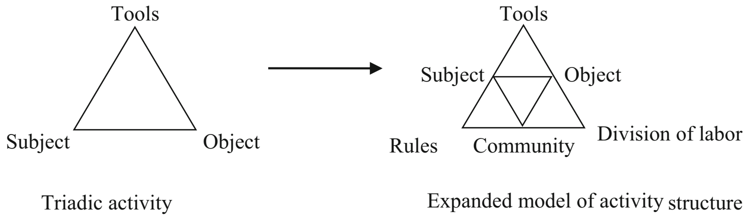

Fig. 9.1 Engeström's (1987) expanded activity structure

head of the technology department and had taught for 5 years in the school. He was one of the pioneering teachers involved in designing the THINK cycle framework. As an anchor in the physics program, he designed all the physics THINK cycles.

Design of the First THINK Cycle

The trigger problem was about a road accident between a Toyota Hilux lorry and a BMW car near a traffic junction, which caused the death of a passenger seated at the back of the lorry after being flung onto the road. Using the concepts of two-dimensional kinematics, students were asked to find out which driver was at fault. In order to simulate a real-life crime scene investigation, "evidences" such as scaled drawings of the accident scene, photographs showing the victim, and information about the vehicles involved in the accident were presented as important clues to the problem. As a final product, the students were to generate a group report and a 10-min presentation to a group of "judges," made up of four physics teachers in the school. The THINK Cycle 1 was carried out over five lessons (a total of 7.5 h).

The Activity System of THINK Cycle 1

The enacted THINK Cycle 1 can be described by five key episodes: (1) presentation of trigger problem, (2) discussion of hypotheses and identification of learning issues, (3) lecture of the concepts of projectile motion, (4) problem solving of practice questions and trigger question, and (5) presentation of solution to trigger problem. In each activity, the focus on mastery of the intended content knowledge as stipulated by the curriculum objectives was evident.

Right from the presentation of the trigger problem, the mastery of content knowledge was emphasized by Mr Chen who stressed on the need to master "physics principles and the math principles" in solving the problem and that "we will test you whether you are really good in physics" during the presentation. The concepts of kinematics were again highlighted when students proposed their hypotheses. Mr Chen gave more attention to ideas related to the intended topics, whereas responses related to traffic rules and road conditions received none other than a cursory acknowledgment. The focus on the content knowledge was most evident during the lecture and problem-solving episodes. Practice problems given to the students to solve closely resembled an earlier example given by Mr Chen. The students merely had to identify the correct numerical values to substitute into equations given to them. Explaining for his actions, Mr Chen said, "I give them a problem so by getting them to tackle the problem, the SIO will have been covered . . .." SIO refers to the specific instructional objectives specified in the GCE "A" level examination syllabus. In a similar vein, during the presentation episode, questions asked by Mr Chen were mainly used to test the students' understanding of two-dimensional kinematics. Evidently, disciplinary content knowledge was the key object of the THINK cycle. This inference was supported by the teacher and students, who rank content knowledge as their top priority during the interview. As echoed by Mr Chen, the objectives of this THINK cycle were primarily to learn "kinematics and projectile motion," all of which were content driven.

With the object of the activity focused on content mastery, the practice and trigger problems functioned as tools. They were used by Mr Chen (1) to direct students' attention to the topic of projectile motion during the generation of hypotheses and learning issues episode, (2) as a form of illustration of the concepts of projectile motion in the worked examples, and (3) to provide the context for applying the knowledge of projectile motion to ensure understanding. Just as the problems were given to ensure that "at least I equalize everyone in terms of the basic understanding of projectile motion," the trigger problem was given as he recognized that not everyone would be able to solve it, "which is why I had one problem a day at the start of the lesson . . . at least to give everyone a chance to think about the problem . . . which are very similar to the CSI." It seemed that the trigger problem was intended as an extended practice.

Mr Chen's actions seemed to be influenced by the importance he placed on the learning objectives for this THINK cycle. During the interview, Mr Chen had ranked the objectives listed in the official syllabus as his top priority. He had specifically emphasized that his main objective was "to get the kinematics projectile motion taught to them." Other objectives, such as "the understanding of the (Singapore's) laws . . . which is not deemed essential to the topic but something good to have," were given less emphasis.

Other mediating factors included the syllabus' objectives and assessment criteria as Mr Chen explained that the first practice question was to help students be "accustomed to resolving vectors, x component and y component, to solve problems" and the second question was "to get them to see that all they had to do is to look at the displacement rather than distance," as he made reference to the vertical displacement of the object in the equation of motion. Furthermore, it was observed that Mr Chen would instruct students on the assessment criteria such as "you will get the negative one penalty," and ". . . whether you know how to do, the first thing I want to see that will probably get you two marks straightaway is . . .." On these remarks, Chen explained that "ultimately the examination is 40 %. . . . in the marking scheme, . . . we mark them based on the steps they give." Therefore, he felt that "the assessment objectives are very important" and "PBL is not very strong in getting them (students) into structures" in terms of procedural steps. As a result, he had to "hammer them with the necessary structures because even in A levels, there is a certain right way of doing things." In other words, Mr Chen's decisions were influenced by the official national curriculum.

In terms of their roles in this THINK cycle, it was clear that Mr Chen was authoritative, while the students took on a more passive role of following the teacher's instructions. Students seldom worked collaboratively together although they were grouped. They seldom sat together, and when they did, it was mostly to help each other in working out the practice questions.

In a nutshell, the activity of the enacted THINK Cycle 1 was influenced by a community made up of a teacher, students, and curriculum planners. Sharing a common objective of mastery of two-dimensional kinematics, trigger and practice problems were used as tools to help students to achieve the learning goals. The subjects' behavior was influenced by the curriculum goals, objectives, and assessment criteria. What resulted from this THINK cycle was a shallow understanding of its concepts and its limited application to solve problems. Figure 9.2 represents the activity system of the enacted THINK Cycle 1.

Contradictions and Tensions in the THINK Cycle 1 Activity System

The enacted THINK Cycle 1 did not resemble the constructivist's features of PBL. Although a contemporary approach to learning was adopted by the teacher and the students, the traditions of a didactic classroom teaching did not seem to be broken. Instead of collaborative problem solving, traditional practices such as lecture and drill and practice remained the dominant forms of work in this classroom. This lack of transformation in the THINK cycle science classroom could possibly be due to the motive driving it.

According to Leont'ev (1978), every activity is driven by a motive; what distinguishes one activity from another is the object, which gives direction to the activity. All actions are hence in relation to this driving force. In Mr Chen's PBL unit, acquiring and mastering content knowledge seemed to be the primary object, and the problems were used merely as tools for reinforcing the content acquired. Engeström (1987) attributed this "strange reversal of object and instrument" in school learning to the historical isolation of school from other societal activities. Calling the school science content knowledge "'A' level peculiar content knowledge," Mr Chen acknowledged that "in 'A' levels, there is a certain right way in doing things." He also added that:

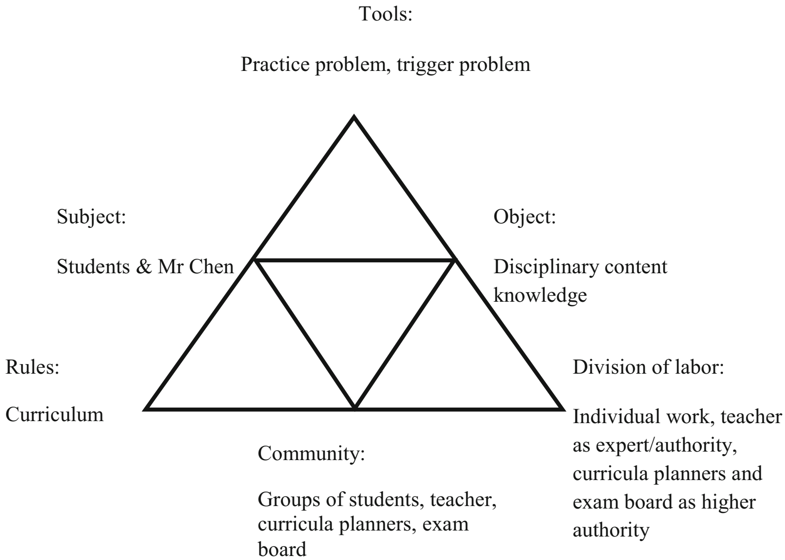

Fig. 9.2 Activity system of the enacted THINK Cycle 1

> certain structures are there in the 'A' level curriculum . . . if you don't show the steps, no matter how good you are and how much you understand . . . the problem or the concepts, you will not do as well as someone who don't know as much but know the structures well.

Therefore, he felt the need to address the importance of examination by "trying to find a system to get the best of both worlds." In other words, although Mr Chen may have the intention to embrace PBL, to him, the motive of schooling is primarily to learn well and succeed in examinations, rather than to seek far transfer to real-life applications.

The lack of transformation could perhaps be explained by the tension between the exchange value and the use value of the object. In the enacted THINK cycle, content mastery is considered essential for getting good examination results, which in turn determines a child's academic path (Lave and Wenger 1991). Problem-solving skills and metacognition are useful and are essential skills in dealing with everyday problems but may not be so crucial in doing well in high-stakes examinations that test mainly recall and procedural knowledge. As mentioned by student SX that while "relating to real world is interesting, it is worrying for exam." Mirroring this concern, Mr Chen said that "PBL will be able to role model better the skills that are required for working life . . . (but) PBL approach is not strong in getting them into structures . . . (which) are there in the 'A' level curriculum." He further commented that "ultimately assessment objectives are very important . . . with current 'A' level, PBL is very difficult to be successful in a big scale." Therefore, to overcome the perceived disadvantage of PBL, Mr Chen stressed that a certain amount of drilling would be necessary.

In a nutshell, the first research cycle identified challenges that teachers and students faced in implementing PBL in science education system, constrained by a national curriculum and an expectation to produce good examination results. Yet, for any true transformation in teaching and learning, PBL has to be the pedagogical base in the curriculum and not part of a didactic curriculum (Savery 2006). To overcome this "lethal mutation" (Brown and Campione 1996) of PBL in the enactment of THINK Cycle 1, considerations will be taken of the contradictions and tensions observed in this first research cycle in the design of THINK cycle, with the hope of bringing THINK cycle to a closer alignment to the PBL approach.

Research Cycle 2

Participants

This second research cycle was conducted with Class 1A in the following year. There were 25 high-ability local students, 9 boys and 16 girls. It was their first experience of THINK cycle since it was the beginning of a new academic year. A group of students, made up of five 14-year-old students, three females (EL, XM, CF) and two males (SH and YH), was identified for the study. The physics teacher of Class 1A was Ms Tam who joined the teaching profession for half a year when Research Cycle 2 was conducted. She had no prior experience in PBL.

Design of THINK Cycle 2

In the second research cycle, a concerted effort was made to align this THINK cycle (to be referred to as THINK Cycle 2 henceforth) to its constructivists' principles. Interventions in its design and implementation introduced include the following: (1) a real-life problem was designed and used as the anchor for all learning activities instead of functioning as a tool for additional practice; (2) learning activities were designed to center on real-life problem-solving practices, rather than a preamble for a lecture on related scientific concepts and principles; (3) collaboration mediated by a computer-supported collaborative learning system, Knowledge Constructor, was introduced instead of individual practice of procedural-based problem solving. A screenshot of Knowledge Constructor environment of one of the forum discussions is shown in Fig. 9.3. To address the teachers' concern about balancing content mastery and development of skills, instructions were specifically given to students to identify learning issues and to work on them as they solved the problem.

Guided by the principles of PBL, the design of THINK Cycle 2 was based on the topic of two-dimensional kinematics. The trigger problem involved a humanitarian

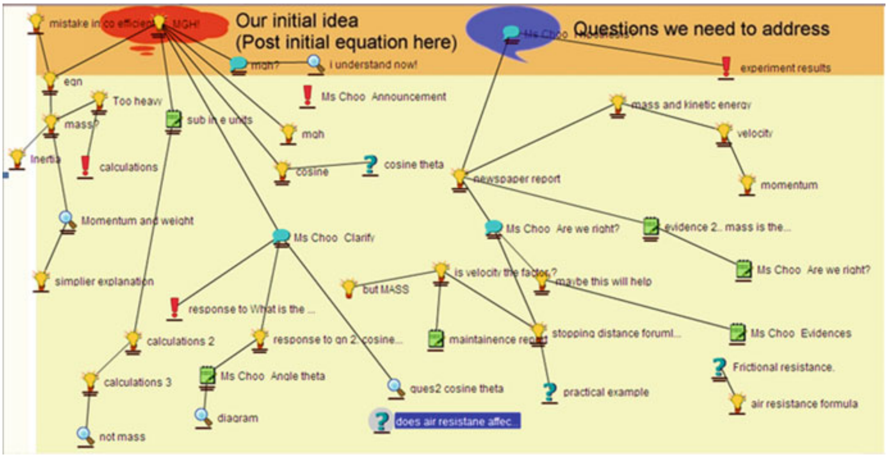

Fig. 9.3 Screenshot of the Knowledge Constructor environment

movement to deliver food items to civilians trapped in a war zone. Assuming the role of controllers of an airplane, the students were asked to find out the most appropriate time to release a package of the food items from the moving airplane. A simulated airplane in the form of a remote-controlled car moving on tracks placed above the ground was set up. A lump of plasticine representing the food parcel was placed in the car. This parcel would be released when a plastic door placed on the base of the car was pulled open by a string that had its other end tied to a fixed structure at the starting point of the car. The students' task was to find out the length of the string that held the "catch door" to the starting point. Figure 9.4 shows the setup of the simulated model plane. Table 9.2 summarizes the design of THINK Cycle 2 according to its five stages.

The Activity System of THINK Cycle 2

The analysis of the interaction data showed the group of five students sharing a common objective of seeking a solution to the given trigger problem throughout the THINK Cycle 2. This is evident from the students' talk on Knowledge Constructor that consisted mostly of proposed solutions. Few learning issues were identified or explored, even though students were specifically told to do so at the start of the activity. Even face-to-face sessions to discuss the ideas posted online consisted mostly of sharing procedural steps, but the students were unable to make use of scientific theories to support their proposed solution most of the time. For example, student YH proposed a seemingly sound solution:

Fig. 9.4 Setup of the simulated model plane

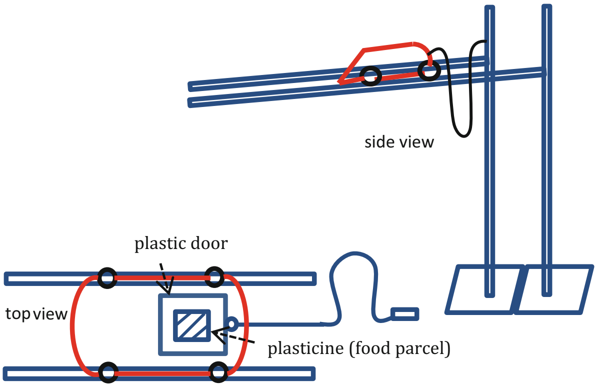

Table 9.2 Design of THINK Cycle 2

Stages	Activities
Trigger	Presentation of trigger problem
Harness	Generation of solution (individual and group), refinement of solution (individual and group), exploration of content knowledge in the context of problem solving
Investigation	Operationalization of group solution
Network	Communication through CSCL system, Knowledge Constructor
Know	Testing of solution through competition, writing of group report, and individual reflection log

Calculate time taken for parcel to drop from height of "plane" to ground
Calculate time taken for "plane" to reach the designated spot
Subtract answer of first question from second question
Find distance from car to starting point at the designated time (answer in third question)
Distance = required length of protruding string

But he was unable to explain his proposed procedure scientifically, other than reiterating that the parcel "will move forward with the same speed as the plane" as a matter of fact. Even though EL raised some content-related questions about the phenomenon, the students were keener to vote for a group solution instead of exploring reasons to explain their solutions.

The focus on solution seemed to compromise the students' learning of the intended content knowledge. Instead of exploring the learning issues to help inform the solution of the problem trigger, the students relied on "more knowledgeable" others for their solution. For example, YH sought the help of his school seniors, while EL's brother helped her solve the problem. While a majority was in favor of YH's solution initially, it was the coteacher's support for EL's solution that resulted in students gravitating toward EL's solution. However, in the actual solving of the problem, students made use of trial-and-error approach to find the length of the string. Ms Tam was eventually disappointed that not much physics was learnt at the end of the THINK cycle.

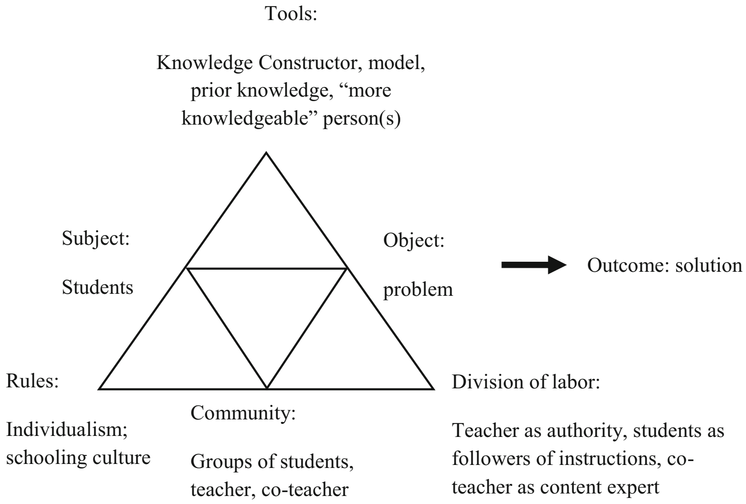

Fig. 9.5 Activity system in the PBL classroom – THINK Cycle 2

In terms of the mediating rules and division of labor, the THINK Cycle 2 was characterized by individualism and passivity instead of collaboration or self-directedness to deepen their understanding of the underlying learning issues. For example, questions raised about the phenomenon were mostly left unanswered. Instead of intersubjective relationship between teacher/coteacher and students, there were signs of power relationship between students and teacher/coteacher. In other words, the students remained as passive learners, while the teachers continued to retain their authoritative status. As a result of the activity, little content knowledge as stipulated by the syllabus was achieved. Figure 9.5 depicts the activity system of THINK Cycle 2.

Contradiction Between Knowledge of "Know-How" and "Know About"

The enactment of THINK Cycle 2 continued to show the contradiction between the kinds of knowledge generated by problem solving and that expected of science learning despite a closer adherence to the principles of PBL. In problem solving, the goal is to successfully resolve the problem. What matters is a kind of knowledge that is called "know-how," knowledge that emerges and manifests itself as part of an ongoing activity (Paavola and Hakkarainen 2005). This probably explained why the group of five students observed was no longer motivated to explore the learning issues further after they found out sufficient knowledge to solve their problem. What resulted was merely functional knowledge.

However, context-specific “know-how” knowledge may not be transferable to other contexts, especially in the context of examination. This is problematic, especially since generalizable and abstract knowledge is the goal of school science learning. This was one of the reasons contributing to Ms Tam’s apprehension when she realized that her students did not use the equations of motion to solve the trigger problem.

The observation in THINK Cycles 1 and 2 seems to resonate with the problems raised by Sfard (1998) about acquisition-based learning and participation-based learning. In the case of an acquisition-based PBL, its transmission approach to transfer knowledge from one mind to another does not provide adequate opportunities for students to participate in science meaning making. Instead, with most of the meaning making done by the teacher as he/she diligently transfers the knowledge he/she has constructed to the students, the only opportunity left for students to engage in meaning making is probably when they are trying to solve problems. Even then, findings in Research Cycle 1 show that the activity can be reduced to mechanical steps as heuristics of solving examination-like questions are explicitly taught to the students. Such acquisition-based approaches compromise on the opportunities for students to be engaged with systems of scientific semiotic resources that are necessary for constructing meaningful knowledge for the students.

The practitioner origin of PBL suggests that the design of PBL falls into the participatory paradigm. Described to be similar to the inquiry practices of scientists (Greenwald 2000), it is said to link students to the essential habits of mind and thought processes of scientific exploration and discovery. However, as shown in this study, its implementation in a high school context may pose a real challenge to teachers and students in trying to achieve the discrete knowledge goals in the science curriculum. In problem solving, it may not bring to the fore the depth of knowledge that underlies the practical knowledge that is eventually applied to solve the problem. Learning may thus be reduced to the functional aspect of know-how, thereby diminishing the opportunities for students to be deeply engaged in making sense of the scientific principles and concepts. The specificity of knowledge constructed as a result of solving problem in a specific context also runs contrary to the need to construct generalized knowledge that can be applied in new situations.

Instead of one or the other, Paavola and Hakkarainen (2005) suggested a third metaphor of learning, knowledge creation, to overcome the content-process divide. Knowledge creation refers to learning environments that emphasize on the continual advancement of the community’s knowledge. These learning environments extend the acquisitive notion of learning by emphasizing not only individual cognition but also the community’s collaboratively development of artifacts (Paavola and Hakkarainen 2005). Learning is, therefore, perceived as a kind of individual and collective activity that goes beyond the information given, focusing on the continual advancement of knowledge and understanding while highlighting the collaborative, systematic development of conceptual and material artifacts at the same time (Paavola and Hakkarainen 2005). Applied to PBL, the principle of idea improvement of community's knowledge could direct students' attention toward seeking continual refinement of the solution sought and collective advancement of the group's knowledge. This could involve students in working on interpreting and transforming the disciplinary knowledge in the context of the problem as they work toward a resolution. This dual emphasis on content and practice holds the promise of affording the construction of generalized knowledge, broadly indexed to the problem situation, thus averting the problem of inert knowledge or narrowly contextualized knowledge often associated with acquisition and participative-based learning environments, respectively (Scardamalia 2002). The principles of epistemic agency and collective advancement of the community's knowledge of a knowledge creation learning environment (Scardamalia and Bereiter 2004) could inform the necessary strategies to scaffold students in collaboration and self-directed learning during THINK cycle.

Research Cycle 3

Participants

The third research cycle involved one physics teacher and her students working on a trigger problem related to the law of conservation of energy. The teacher, Ms Cho, who is a physics graduate, had been one of the collaborating teachers in the research. A recent graduate (about 1 ½ years) from the teacher's teaching institution, she had volunteered to participate in the research. It was her second year teaching the THINK cycle. The group of students in this study consisted of four girls (D, J, XC, and K) and one boy (M) of 14 years of age.

Design of THINK Cycle 3

Conscious of the content-process tensions in the previous cycles, the design of this THINK cycle (which will be referred to as THINK Cycle 3) was guided by principles of knowledge creation that emphasized collective advancement of cognitive and material artifacts. With a trigger problem involving a fictitious roller-coaster accident in an offshore island in Singapore, students were tasked to investigate the cause of the accident in groups of five. Supporting the students in a more structured manner, students were directed to (1) construct a mathematical expression to explain how the roller coaster worked during the harness stage and (2) create and test their hypothesis during the investigation stage.

The construction of a generalized expression to explain the roller-coaster ride was to address the potential absence of generalizable theory in mediating problem solving that was observed in the second research cycle. The creating and testing of hypothesis support students' engagement in the meaningful use of theory in problem solving. A model of the last section of the ride where the accident happened and "evidence" gathered from the scene of the accident such as newspaper reports, police reports, and maintenance reports were also provided to mediate this problem-solving process. The structuredness of this THINK cycle was to support students with self-directed learning that was absent in the second research cycle.

In alignment with knowledge creation, students were encouraged to build on one another's ideas and make revisions to existing ideas. For example, they could return to the harness stage to refine their theory of the roller coaster's motion or refine their experimental design if their hypothesis was not supported. In this sense, the principle of idea improvement was built in. Throughout the process of THINK cycle, the students would network with one another via face-to-face and online platforms. Knowledge Constructor continued to provide the technological platform in this THINK cycle to mediate students' collaboration.

The Activity System of THINK Cycle 3

Two main activity systems were found in the enactment of THINK Cycle 3: knowledge building and problem solving. The two activity systems were found to be closely related to the other, with the outcome of each activity supporting the other, even though the object for each of the activity system was different.

The knowledge-building activity was enacted in the harness stage. It involved students building an expression to describe how the roller-coaster ride worked. Two instances of knowledge building were observed, with the first being orchestrated by the teacher. The first instance took place when the students were trying to explain "how friction affects the point in which the car stops?" A search on the Internet led to a large amount of information, albeit detached from the problem context, copied onto the Knowledge Constructor. To direct the students to apply the information to the problem context, Ms Cho prompted the students with three questions, "1. Why/how does the cart start to move down the slope?" "2. Why does it come to a stop?" "3. How do we find the stopping distance?" These three questions led the students to think about the information they found on the Internet and applied it to the problem context to derive an expression to describe how the roller coaster worked. This derivation eventually led them to hypothesize the cause of the accident.

A second instance of knowledge building took place when the students, in testing their hypothesis with the model setup, found that their results were contradictory to the theoretical results they expected to find. This time, they took their own initiative to examine at their interpretation of the problem context in the light of the scientific knowledge they found. The result was a refinement of their understanding of the problem context, in terms of the assumptions made. The social processes observed during this knowledge-building activity included sharing of information as each student posted the information they had found on the Internet,

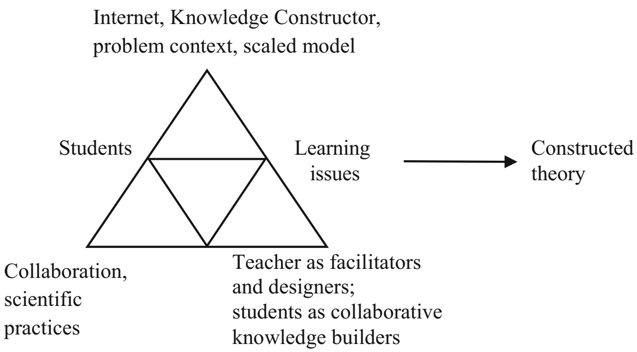

Fig. 9.6 Activity system for construction of expression for the roller coaster

negotiation of information found on the Internet, and interpretation of the work-energy theorem in the context of the problem. The participation structure observed from the interaction data also showed signs of collaboration among the students in the knowledge-building process as the students built on one another's ideas by elaboration or argumentation. This activity resembles the kind of theory-building activity that Scardamalia and Bereiter (2003) advocate, whereby continuous advancement of context-general knowledge distinguishes the activity from other content-focused learning activity. Figure 9.6 shows the activity system for this model construction activity.

The problem-solving activity was enacted during the investigation stage. When the students had derived an expression describing the motion of the roller coaster derived, they studied the "evidences" created by the teacher and research team to hypothesize the cause of the accident. In this case, the students hypothesized that the excessive weight of the roller-coaster ride was the cause of the accident. They then gathered evidences to support their hypothesis experimentally and theoretically. Experimentally, they made use of the model setup to test the stopping distances for different mass in an attempt to find out the relationship between stopping distance and mass. They tested their theory by making use of the data provided in the "evidences" and the derived expression to find out if the results concur with the empirical data. To their surprise, the two results contradicted. This led them to another round of knowledge building as described earlier.

In short, the problem-solving activity had the problem of the roller-coaster accident as its object. Mediating this activity were the derived expression constructed during the modeling activity, the evidence created by the teachers and researchers, and the model setup. In this process, the students played a significant role in solving the problem. Online discussion data showed the students sharing their interpretation of the evidences, negotiating possible factors that might have caused the accident, and interpreting the derived equation in the context of the problem. The outcome of the problem-solving activity was more puzzling questions that triggered another episode of knowledge building. In the second cycle, a

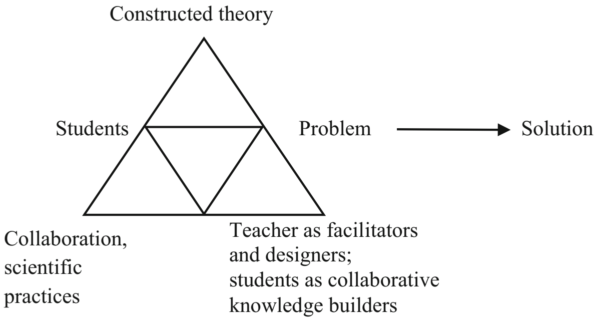

Fig. 9.7 Activity system for problem solving

solution was finally found. Figure 9.7 shows the activity system for problem solving.

While each activity could be associated with an activity system on its own, each serving different objects, the enactment of THINK cycle in this research cycle shows that they are closely connected. The derived expression constructed during the knowledge-building activity served as the mediating tool for problem solving. The process of problem solving, in turn, provided the impetus for further advancement of knowledge as students were puzzled by the discrepancy in their findings. In other words, the two processes were closely coupled despite the differences in their focus.

Therefore, to represent the activity of the enacted PBL, we used two activity systems, one to represent knowledge building and another to represent problem solving, to illustrate the different focus of each activity and their interdependence on each other. Figure 9.8 shows the components of each activity system and their interdependence in this THINK cycle.

Overcoming the Content-Process Divide with Knowledge Creation

In refining the PBL process, findings in the first two research cycles indicated a constant tension between the roles of content and problem. In an acquisition-based PBL, the strong emphasis on acquisition of content knowledge reduces the role of problem to that of a tool to ensure that the acquired knowledge can be transferred reliably to examination-like questions through a mechanical application of a set of rules and heuristics. On the other hand, a participation-based PBL foregrounds the problem-solving process so much that knowledge fades into the background. Appropriation of knowledge is assumed to happen through the embodied act of doing.

It is in this respect that the introduction of the notion of knowledge creation seemed to resolve the tension between content and process. The third research cycle shows that problem-solving activity could trigger puzzling problems for knowledge

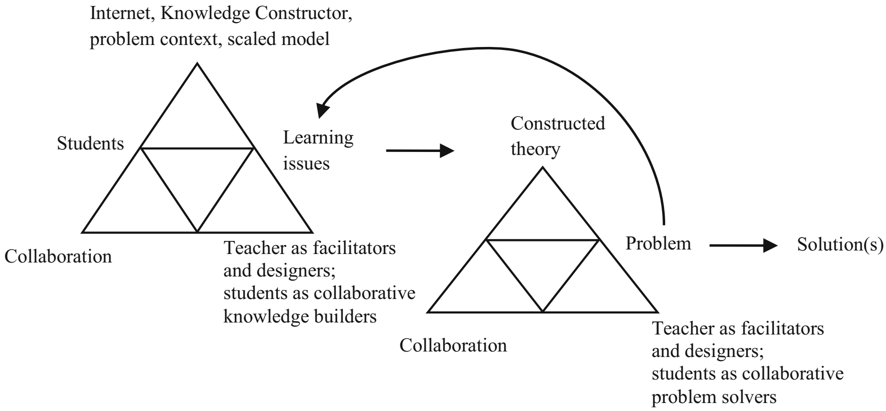

Fig. 9.8 Interdependence between theory-building activity system and problem-solving activity system

building, while the outcome of knowledge building provides the tools needed for meaningful problem solving. In other words, the findings of this study show that the problem-solving and knowledge-building processes are codependent as the absence of any one of the processes will restrict the goal to either content mastery or problem solving. The interdependence between the two processes implies that each functions as a tool for the other and also as a focus of attention in its own activity. Without problem solving, the knowledge constructed in the knowledge-building activity has no functional use, therefore rendering the activity to lose its use value. With the absence of knowledge building, problem solving may be reduced to haphazard trial and error or mere functional know-how, which may not be generalizable to other situations, thereby reducing the usefulness that a problem-solving activity may provide. While this study has not shown that the knowledge resulting from THINK Cycle 3 may be generalizable to other problems, the kinds of knowledge constructed make application more probable than in THINK Cycles 1 and 2. Therefore, the integration of the two activity systems in PBL situated in the knowledge creation paradigm provides an effective bridge between the tension observed between content and problem.

Discussion and Conclusion

The purpose of this study is to refine the pedagogical approach of PBL to support science meaning making more effectively through three cycles of design research. Through the three research cycles, three designs of THINK cycles were observed. THINK Cycle 1 was a linear enactment of the five stages of presentation of trigger, lectures of intended disciplinary content knowledge, practicing on given problems and trigger problem, and, finally, presentation of solution. The enactment did not

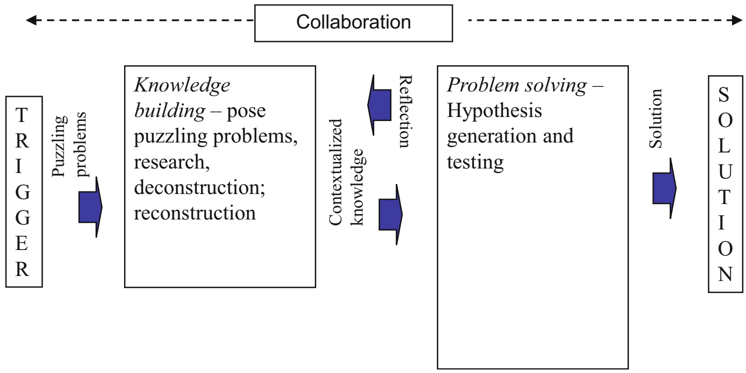

Fig. 9.9 Knowledge creation-based PBL framework

result in deep understanding of the knowledge, development of skills, or any significant transformation in pedagogical approach. The reason was traced to the contradiction between content and process as the teacher and students were torn between a focus on mastery of disciplinary content knowledge for examination purpose and development of problem-solving and learning skills. The design of THINK Cycle 2 was intended to return to the constructivist's roots of PBL. The problem trigger formed the center of the activity. The result was a strong focus solving the problem, with exploration of learning issues observed during the harness stage. Students also did not seem to collaborate effectively with one another. In the THINK Cycle 3, the principles of knowledge building were introduced; in particular, the advancement of knowledge was introduced as its motive. Instead of a linear enactment of the five stages of PBL, the knowledge creation framework integrates the processes of knowledge building and problem solving to orchestrate science meaning making, with an iteration between knowledge building during the harness stage and problem solving during the investigation stage. Figure 9.9 describes the framework of this knowledge creation-based PBL.

Supporting this knowledge creation activity are a collaborative setting, authoritative sources, and the problem context. It was found that students were able to develop a deeper understanding of the intended disciplinary content knowledge and were able to work collaboratively with one another in the problem solving. Table 9.3 summarizes the design and contradictions observed in each research cycle.

The three research cycles revealed how science meaning making could be supported. The first two research cycles showed that neither focusing on knowledge nor social processes in PBL seemed to support science meaning making in high school adequately. Rather, a focus on the transformation of knowledge through social processes of learning provides the structure needed for science meaning making to take place. In this respect, the principles of knowledge building provided the mediating structures to support students developing meaningful and creative use of knowledge in the service of problem solving. The principle of advancement of knowledge helped to direct students' attention toward developing a deeper

Table 9.3 A summary of the design and contradictions of each research cycle

	Cycle 1	Cycle 2	Cycle 3
Key design features of the instructional approach	Lecture and drill and practice of intended content knowledge	Trigger problem as the center of activity	Emphasis is placed on advancement of cognitive artifacts – content and solution
	Problem trigger provided as additional practice for the intended content knowledge	Exploration of learning issues was encouraged through problem solving	Structuredness in theory building and problem solving to support students' self-directed learning
		Collaboration was mediated through the use of Knowledge Constructor	Collaboration was mediated through the use of Knowledge Constructor
Contradictions identified	Content-process divide: pedagogical approach remained didactic despite that a constructivist approach was adopted. This was due to a strong focus on content mastery over the development of problem-solving skills	Content-process divide: a stronger adherence to the principles of PBL resulted in students focusing excessively on arriving on the solution without much exploration into the intended content knowledge to learn. Students were unable to direct their attention on pertinent learning issues and lacked the skills to collaborate effectively	
Interventions to be introduced to the next THINK cycle	Returning to the roots of PBL by engaging teachers and researchers to work jointly in understanding and designing PBL activities	Introduction of KB principles – collective knowledge advancement and epistemic agency	

understanding and use of the intended disciplinary content knowledge in the context of problem solving. In addition, the focus on theory building during the harness stage and problem solving during the investigation stage seemed to provide the structure for students to overcome the difficulties of directing their attention on learning issues and problem solving during the THINK cycle activity.

Besides showcasing the principles of knowledge creation in the design of THINK cycle, this study also aimed to construct and refine the theory of PBL. Through design research, the model of PBL for school science learning was constructed and refined through the three research cycles. The analytical lens of

CHAT provided the framework for this expansive learning (Engeström 1987) of PBL.

Finally, as a case study within a design research, further studies need to be conducted to better understand the necessary supports needed to mediate students' learning in science better. Further theorizing and empirical research are needed to refine the proposed framework of PBL and to deepen our understanding of how PBL supports science meaning making.

References

Albanese, M. A., & Mitchell, S. (1993). Problem-based learning: A review of the literature on its outcomes and implementation issues. *Academic Medicine, 68*, 52–81.

Angeli, C. (2002). Teachers practical theories for the design and implementation of problem-based learning. *Science Education International, 13*(3), 9–15.

Bereiter, C., & Scardamalia, M. (2003). Learning to work creatively with knowledge. In E. De Corte, L. Verschaffel, N. Entwistle, & J. van Merrienboer (Eds.), *Unravelling basic components and dimensions of powerful learning environments* (EARLI advances in learning and instruction series, pp. 5–68). Oxford: Elsevier Science.

Bereiter, C., Scardamalia, M., Cassells, C., & Hewitt, J. (1997). Postmodernism, knowledge building, and elementary science. *The Elementary School Journal, 97*, 329–340.

Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *The Journal of the Learning Sciences, 2*, 141–178.

Brown, A. L., & Campione, J. C. (1996). Psychological and the design of innovative learning environments: On procedures, principles, and systems. In L. Schauble & R. Glaser (Eds.), *Contributions of instructional innovation to understanding learning* (pp. 289–325). Hillsdale: Erlbaum. New York: Cambridge University Press.

Design-based Research Collective. (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher, 32*, 5–8.

Douchy, F., Segers, M., Van den Bossche, P., & Gijbels, D. (2003). Effects of problem-based learning: A meta-analysis. *Learning and Instruction, 13*, 533–568.

Engeström, Y. (1987). *Learning by expanding: An activity-theoretical approach to developmental research*. Helsinki: Orienta-Konsultit. Retrieved from http://lchc.ucsd.edu/MCA/Paper/Engeström/expanding/toc.htm

Engeström, Y. (1999). Activity theory and individual and social transformation. In Y. Engeström, R. Miettinen, & R. L. Punamaki (Eds.), *Perspectives on activity theory* (pp. 19–38). Cambridge: Cambridge University Press.

Gallagher, S., & Stepien, W. (1996). Content acquisition in problem-based learning: Depth versus breadth in American studies. *Journal for the Education of the Gifted, 19*, 257–275.

Greenwald, N. (2000). Learning from problems. *The Science Teacher, 67*, 28–32.

Hill, A. M., & Smith, H. A. (2005). Research in purpose and value of the study of technology in secondary schools: A theory of authentic learning. *International Journal of Technology and Design Education, 15*, 19–32.

Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn? *Educational Psychology Review, 16*, 235–266.

Kozulin, A. (1986). The concept of activity in Soviet psychology: Vygotsky, his disciples and critics. *American Psychologist, 41*, 264–274.

Lave, J., & Wenger, E. (1991). *Situated learning; Legitimate peripheral participation*. Cambridge: Cambridge University Press.

Lee, H., & Bae, S. (2008). Issues in implementing a structured problem-based learning strategy in a volcano unit: A case study. *International Journal of Science and Mathematics, 6*, 655–676.

Leont'ev, A. N. (1978). *Activity, consciousness, and personality*. Englewood Cliffs: Prentice-Hall.

Liu, M., Hsieh, P., Cho, Y., & Schallert, D. L. (2006). Middle school students' self-efficacy, attitudes and achievement in a computer-enhanced problem-based learning environment. *Journal of Interactive Learning Research, 17*, 225–242.

Mergendoller, J. R., Bellisimo, Y., & Maxwell, N. L. (2000). Comparing problem-based learning and traditional instruction in high school economics. *The Journal of Educational Research, 93*, 374–382.

Miettinen, R. (1999). Transcending traditional school learning: Teachers' work and networks of learning. In Y. Engestrom, R. Miettinen, & R. L. Punamaki (Eds.), *Perspectives on activity theory* (pp. 325–344). Cambridge: Cambridge University Press.

Mortimer, E., & Scott, P. (2003). *Meaning making in secondary science classrooms*. Maidenhead: Open University Press.

Paavola, S., & Hakkarainen, K. (2005). The knowledge creation metaphor – An emergent epistemological approach to learning. *Science & Education, 14*, 535–557.

Savery, J. R. (2006). Overview of problem-based learning: Definitions and distinctions. *The Interdisciplinary Journal of Problem-based Learning*, *1*, 9–20. Retrieved from http://eric.ed.gov/ERICWebPortal/contentdelivery/servlet/ERICServlet?accno=ED482724

Savery, J. R., & Duffy, T. M. (1996). Problem based learning: An instructional model and its constructivist framework. In B. Wilson (Ed.), *Constructivist learning environments: Case studies in instructional design* (pp. 135–148). Englewood Cliffs: Educational Technological Publications.

Savery, J. R., & Duffy, T. M. (2001). *Problem based learning: An instructional model and its constructivist framework* (CRLT Technical Report No. 16–01). Bloomington: Indiana University.

Scardamalia, M. (2002). Collective cognitive responsibility for the advancement of knowledge. In B. Smith (Ed.), *Liberal education in a knowledge society* (pp. 67–98). Chicago: Open Court.

Scardamalia, M., & Bereiter, C. (2003). Knowledge building. In J. Guthrie (Ed.), *Encyclopedia of education* (pp. 1370–1373). New York: Macmillan Reference, USA.

Sfard, A. (1998). On two metaphors for learning and the dangers of choosing just one. *Educational Researcher, 27*, 4–13.

Sonmez, D., & Lee, H. (2003). *Problem-based learning in science*. ERIC digest (Report No. EDO-SE-03-04). Columbus: ERIC Clearinghouse for Science, Mathematics, and Environment Education. (ERIC Document Reproduction Service No. ED482724). Retrieved from http://eric.ed.gov/ERICWebPortal/contentdelivery/servlet/ERICServlet?accno=ED482724

Varela, F., Thompson, E., & Rosch, E. (1991). *The embodied mind*. Cambridge, MA: MIT Press.

Vernon, D. T. A., & Blake, R. L. (1993). Does problem-based learning work? A meta-analysis of evaluation research. *Academic Medicine, 68*, 550–563.

Vygotsky, L. (1978). *Mind in society: The development of higher psychological processes*. Cambridge, MA: Harvard University Press.