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Promoting Model-based Reasoning in Problem-based Learning

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Abstract

We have been observing a problem-based learning class (PBL) in a biomedical engineering program (BME). The present paper examines the learning trajectory in which students attempted to solve a complex and genuine research problem in BME, and attempts to unpack the dynamics of problem-based learning, identify the links between different sub-components in the problem-solving process, and document specific instructional moves that would strengthen such links by promoting model-based reasoning (MBR). We found that through PBL students can successfully build skill in model-based reasoning, a significant cognitive practice used in BME. It is also critical to the learning process that the PBL facilitator could speed up the learning process and help students acquire skills of model-based reasoning by scaffolding at the process but not the content level, and constantly prompting students with a holistic and coherent view of the models in the problem.

Introduction

Problem-based learning (PBL) was first designed to support the development of hypothetico-deductive reasoning in medical education. In PBL, students learn by reflecting on their own experiences, conducting self-directed search, integrating information from multiple disciplines, and solving realistic but often ill-structured problems (Barrows, 1985; Barrows and Tamblyn, 1980; Cognition & Technology Group at Vanderbilt 1994; Collins, Brown, & Newman 1989; Hmelo-Silver, 2004). The success of PBL has prompted researchers to systematically evaluate the effectiveness of learning by identifying the unique properties of PBL (compared to the traditional more passive forms of instruction) and the conditions where learning actually occurs (e.g., Capon & Kuhn, 2004; Cornelius & Herrenkohl, 2004; Hmelo-Silver, 2004; Hmelo-Silver & Azevedo, 2006; Polman, 2004).

Our primary interest in the present study is to unpack the dynamics of problem-based learning, identify the links between different sub-components in the problem-solving process, and document specific instructional moves that would strengthen such links by promoting model-based reasoning (MBR), and to find out whether and how this learning environment supports the development of model-based reasoning in complex problem solving. As a growing body of research in history and philosophy of science establishes, model-based reasoning is a signature feature of much research in the sciences, both in discovery and application (Cartwright, 1983; Giere 1988; Hesse 1963; Magnani, Nersessian, and Thagard 1999; Morgan and Morrison 1999; Nersessian 1999, 2002, 2005)

By model-based reasoning, we mean constructing representations (e.g., tables, diagrams, abstract hypothesis), in the form of a model (e.g., physical models, mathematical and statistical models) and deriving inferences through manipulation of the model through abstraction, simulation, adaptation, and evaluation. The examples of utilizing model-based reasoning would include dimensions such as: role of ideas, use of symbols, role of the modeler, communication, testing models, and multiplicity (Grosslight et al., 1999), and serve functions such as description of a natural process, explanation and prediction, assessment of the models by the empirical and conceptual criteria, and guidance to future research (Cartier, Rudolph, & Stewart, 2001).

We have been studying several PBL classes in a biomedical engineering (BME) program where students learn to apply engineering principles and reasoning strategies to complex, open-ended BME problems with the support and guidance of a group tutor/facilitator. These classes typically have around 100 to 160 students, who meet once a week all together for lectures and twice a week in small groups (8 to 9 students) for problem-solving. This example we develop here is based on observation of one PBL group for one semester (fifteen weeks). In the following extended example, we examine the learning trajectories, identify the distinct characteristics of the learning process that demand model-based reasoning strategies, and illuminate the reciprocal relationship between problem-based learn and model-based reasoning.

Before we get to the problem, it is necessary to point out that the unique role of the group facilitators as they assisted students in developing versatile and informed model-based practices and helped students learn both content and thinking strategies, for instances, promoting the usages of tables, diagrams, and matrices of comparisons whenever appropriate (e.g., Newstetter, 2005). We observed the facilitator supporting the development of MBR in all dimensions mentioned above by scaffolding at the process not the content level. Figure 1 illustrates the role of a facilitator in problem-based learning, as compared to teacher-driven instruction. In the conventional classroom, the instructor teaches refined models to the students. In PBL, students are encouraged to develop models and then refine them, thereby learning how models explain phenomena, clarify complicated concepts, work as hypotheses, and integrate pieces of information from multiple disciplines.

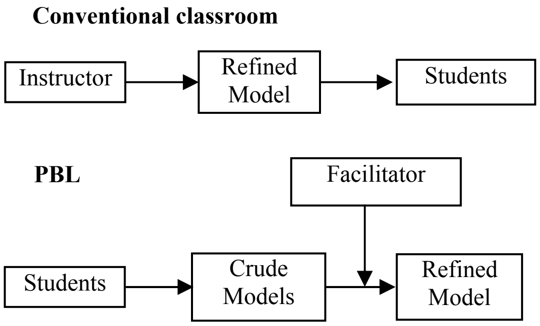

Figure 1. The role of facilitator in PBL

The Pedometer Problem

The PBL class discussed here was redesigned to foster and, demand the kind of utilization and engagement with models that is found in both research practices and ideally in learning. The class of mostly freshman in BME was divided into small groups of eight/nine students. Each semester, the groups are given three problems to solve, each lasting about five weeks. At the beginning of each problem, the students were given only minimal instructions besides the problem statement. They were instructed to collaborate in groups, to work out a solution or solutions to the problem, then, present their findings to the entire class and the facilitators who are the faculty members in BME. These small groups meet twice weekly and each has a facilitator.

The data collected from the PBL class included problem statements, video footage of the meeting sessions, images captured on the whiteboard, handouts made by students and facilitators, PowerPoint presentations by students, and the final written report for each problem. It also included a pre- and post-questionnaire on recognizing instances of MBR that we designed.

The following was an abstract of the second problem given to the students during our observation:

> *... The 10,000 Steps Program ... is designed to encourage people to reach a daily goal of walking or running 10,000 steps. Program participants use a pedometer to monitor their activities and get feedback. However, there have been concerns over the accuracy, reproducibility and repeatability of measurements made with pedometers.*
>
> *Your group is challenged to develop a hypothesis for identifying a factor, other than device malfunction or user misuse, which contributes to one of a pedometer's low performance characteristics (e.g., accuracy, reproducibility or repeatability). You will then develop an experimental design to test that hypothesis. Your hypothesis should be formed based on a thorough study of both the physiology behind body measurements and the sensor technology employed in your device. Your experimental study, to be conducted with a pedometer purchased by your group, must be designed to use the number of human subjects necessary to produce statistically significant results.*

An "Ideal" Work Flow

Hmelo-Silver (2004) depicted a typical learning circle of PBL, also known as the PBL tutorial process, in which students formulate and analyze the problem by going through stages of identifying facts, generating hypotheses, identifying knowledge deficiencies, applying new knowledge, abstraction, then going back to the initial stages for evaluation. Given the fact that the nature of the pedometer problem is experimental design and hypothesis testing, a similar learning circle can be drawn as in Figure 2.

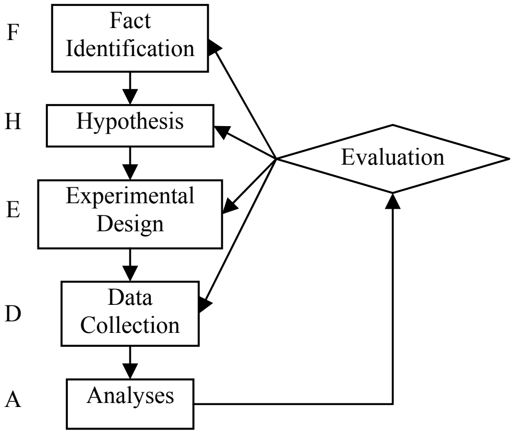

Figure 2 An ideal work flow

As stated in the problem, students first need to identify the factors that affect the performance of the pedometer. In terms of experimental design, it is to identify the appropriate dependent variables and independent variables, then, to formulate a hypothesis or hypotheses about the statistical relationships between these variables. Then, the experimental conditions are planned and experimental protocols are developed. Once the experiment is carried out and the data are collected, statistical analyses are conducted.

Apparently, the learning process depicted in Figure 2 is only an idealization. In the actual PBL environment, such process will never be completed in such a *linear* fashion. Although it is depicted in a top-down single direction, every building block in Figure 2 has to be supported or constrained by the block below. For example, to be able to efficiently identify relevant factors, students have to first understand the purpose of a hypothesis, e.g., to identify the correlational or causal relationships between those factors. If the students do not have sufficient understanding of the required statistical tools, experimental design would not be completed in a single pass. It is very likely that after spending some time in planning the experimental conditions, students realize that they do not have an appropriate hypothesis. Then the iteration would have to be started again somewhere. As we can see in the next section, this is exactly what we have observed in the class. In the following, we lay out the actual learning trajectory that occurred during our observation.

Actual Problem Solving Trajectory

It took 10 meeting sessions for students to finally finish this particular problem (they met twice a week and each meeting lasted 90 minutes). After 6 sessions into the problem, students gave a presentation on their experimental design to the entire class and received feedback from facilitators. At the end of the 10 meetings, students gave a presentation and turned in a technical report. Due to the limited space of the present paper, we cannot report all of the class activities here. Instead, , we list a series of significant events or the class discussion topics and encode them into one of the building blocks in Figure 2: Fact Identification (F), Hypothesis Formulation (H), Experimental Design (E), Data Collection (D), and Analyses (A). We number these events or topics as they occurred chronologically. For example, 1E then 2A denote a discussion on experimental design followed by a discussion on statistical analyses. Sometimes a topic lasted only ten minutes, while sometimes a topic could last the entire meeting session. Events with an asterisk denote the place where the facilitation occurred.

There are several considerations for such encoding. First it reflects the class activities as a group, not as individuals. Whereas every individual participant contributed to the discussion, only the events in which the entire group participated are reported here. Furthermore, it is important to note that sometimes a discussion served multiple purposes. For instance, literature search can provide information for both Fact Identification and Hypothesis Formulation. In this case, only one of the categories was labeled depending on the result of the discussion, for example, whether the discussion merely led to a list of factors (Fact Identification) or a statement in which the statistical relationship between the variables was specified (Hypothesis Formulation). Another fact that needs to be considered is that the following trajectory leaves out many trivial steps that are less relevant to our primary interest, such as whether to buy the pedometer online, or where to conduct the experiments.

The following is a partial list of encoded activities from one of the PBL groups, where a code (such as 1E, 2A) is followed by a brief description of the event or the discussion topic:

1E: the number of human subjects needed;
2A: the meaning of statistical significance;
3F: criterion of selecting a pedometer;
*4F: What is accuracy, reproducibility or repeatability?
5H: What is the null hypothesis (reviewing statistics);
6F: potential factor (physiological characteristics, stride length, body-mass index, …);
7F: mechanical properties of pedometer;
*8H: hypothesis, version 1: the more false movements, the mover over-count;
9F: literature search: an existing study that looked at the placement of pedometer (hip vs. thigh) and body-mass index;
*10E: using a table to summarize experimental conditions (mimicking the existing study);
*11H: students realized that they did not have their own independent variables and hypothesis yet;
12F: piezoelectricity (the electronic properties of the pedometer);
13F: considering the other two dependent variables (repeatability and reproducibility);
14H: hypothesis version 2: walking speed and placement of the pedometer affect accuracy;
*15E: experiment design with control groups (using clicker to count the actual steps);
…
*20H: hypothesis version 3: "speed has greater / less effect on accuracy than irregular steps";
*21E: a design with a missing condition;

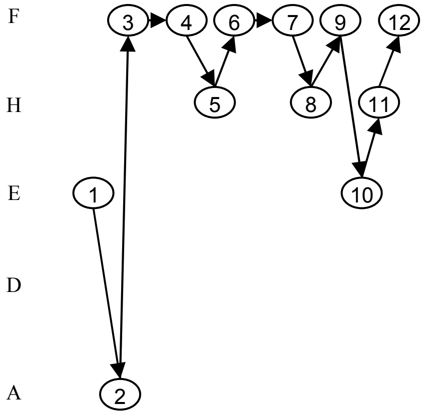

Figure 3 Actual learning trajectory

Figure 3 illustrates the trajectory in which the first twelve steps in the list are plotted sequentially. Compared to Figure2, Figure 3 shows a significant contrast. From the recorded activities, we have identified many interesting characteristics of the learning process in this PBL group. In the following, we discuss four of them. First of all, the final solution to the entire problem was put together by very small pieces like a big puzzle. The learning process started with a most trivial detail that randomly emerged, rather than from a systematically planned workflow. For instance, in 1E, the number of human subjects needed in the experiments appeared in the discussion at the very beginning. In a more conventional instruction-driven classroom, or, if the students were well prepared in experimental design before the PBL class, this topic would have to come very late, at least after a testable hypothesis is developed.

Second, the learning trajectory in Figure 3 is far from a linear process as depicted in Figure 2. It was rare for a small topic to be finished in a single pass. The discussion usually did not follow a single direction, and it was common for the topic to jump back and forth. Each time a small piece of information was added, some of the previous sub-solutions would be revisited and modified (for example, the iteration between fact identification and hypothesis formulation in Figure 3).

Third, some of the links appeared to the more difficult than others. The most obvious example was the formulation of a hypothesis, which endured at least four major revisions throughout the process. The experimental design also suffered as a consequence of the ill-formed hypothesis (e.g., 20H and 21E). As we will demonstrate below, a major intervention had to be introduced to break out of the faulty cycle.

The fourth feature we want to bring to readers' attention shows another significant contrast to the learning in the traditional more passive forms of instruction. That is, partial solutions were achieved not by starting with the most basic concepts, but by using concrete examples and sometimes mimicking existing solutions. For example, when developing their own experimental design, students borrowed the whole paradigm from an existing study (e.g., in 9F and 10E), including the original independent variables. It was only in later stages that these "shell variables" were replaced by the factors identified from their own findings. We reasoned that this practice was because students had little or no prior training in statistics and yet, this turned out to be an effective way of learning as these "shell variables" helped students carry out the discussion on other topics (such as selecting a pedometer for the experiment) without getting detoured in every detail.

Since the students did not possess a complete knowledge structure for each of the components depicted in Figure 2 they had particular difficulties at the fact finding and hypothesis formation stages. Figure 4 illustrates that to be able to efficiently conduct Fact Identification, one has to understand the purpose of the search: to identify the causal relationships between the independent variables and the dependent variable so that a feasible hypothesis could be formulated. Learning occurs through multiple iterations between these two stages until the structure in Hypothesis Formulation is sufficient enough to support the search in Fact Identification.

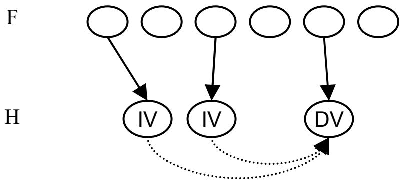

Figure 4 Fact Identification and Hypothesis Formulation

It is necessary to point out that the learning trajectory depicted in Figure 3 might be unique for the particular PBL group documented here. For example, not every group would have the same starting path such as 1E – 2A –. Nevertheless, it is common that for almost all of the groups the formation of hypotheses would take multiple iterations such as that depicted in Figure 4. This observation suggests the essential role of the statistical models (Hypothesis Formation) in the entire problem-solving process, which demands effective facilitation at several different locations. Given the large scale of the problem and the limited time and resources, it is very challenging for the students to work towards a solution and organize the obtained information at the same time. When pieces of seemingly unconnected information are gathered and the discussion topic jumps back and forth, it is very hard for students to see the big picture. Thus, from time to time, it is important for the facilitators to prompt students with a holistic, coherent view of the bigger model of the problem and to provide the links or inter-locks between small pieces of sub-solutions, in a sense, sub-models. Scaffolding for these inter-locks can be provided in different ways. For example, one effective strategy was to prompt students to draw cartoons, diagrams or graphic depictions of phenomena they were trying to understand and apply to the problem (i.e., produce a qualitative model of the phenomena). They were encouraged to articulate provisional hypotheses in the form of statements or visual and graphical depictions of the problem situation, as they understood it. Principles or assumptions that seemed to be guiding their process were explicitly written on the boards, and in many occasions were summarized in tables and matrixes.

It is also important to note that this kind of facilitation was sometimes provided more explicitly and sometimes more implicitly. For example, the facilitator might ask, "can you write an equation to operationalize the term 'accuracy'?" Or, "why don't you draw a picture on the board (to show the mechanism underlining piezoelectricity)?" Or, "What is your hypothesis regarding the walking speed and the performance of the pedometer?" These explicit requests would have pushed students into the desired path by pointing to the key components of the holistic model, such as diagrams, equation, and hypothesis. An example of implicit prompting was when the "shell variables" have served their purposes (e.g., 9F and 10E) and the facilitator felt the discussion should be moved to the next level, she simply asked the students, "Have you identified your own factors to be used as the independent variables?" In this way, the facilitator "peeled off" the shells and revealed that the true purpose of this part of the discussion was to learn the nature of experiment design, not to merely study the effects of body-mass index on the accuracy of a pedometer. In the meantime, students were given as much freedom as possible to search the problem space by themselves, thus, both content and thinking strategies would be more firmly grasped through the learning process.

Thinking in Graphics

To make our claim more convincing, we provide an example where facilitation was achieved by prompting students to draw graphs on board, or, "to think graphically," to represent the statistical model in problem-solving. In 20H and 21E, students reached a stage where they had selected the dependent variable (accuracy) and the independent variables (walking speed and gait) but could not form the hypothesis correctly thus could not render an experimental design. Students were very clear that they wanted to study the effects of speed and gait on the accuracy of the pedometer. However, the hypothesis they had at that moment was:

> "Speed has greater / less effect on accuracy than irregular steps."

Note that without constraining those two independent variables, speed and gait, into a comparable scale (for example, in a reasonable range of daily exercise), this hypothesis was not much different from comparing apples and oranges. Suffering from this ill-formed hypothesis, their experimental design was also ill-structured as in Table 1:

Table 1: An ill-structured experiment design

	Slow	Natural	Irregular
Pedometer			
Clicker (control)			

Note that in Table 1, the condition "slow" meant "slow speed and regular gait," "natural" meant "normal speed and regular gait," and "Irregular" meant "normal speed and irregular gait." On the surface, students were trying to follow the principle of "vary one variable at a time" whereas there was in fact one experimental condition "slow speed and irregular gait" missing. At this point, the facilitator made several requests to speed up the learning process by breaking out the faulty circle, both implicitly and explicitly. The first question asked by the facilitator was,

> "Can you draw a graph to predict the results from your experiment?",

to which the students responded with a bar graph with three columns corresponding to the three conditions in Table 1. It was the next several requests made by the facilitator that helped the students realize that their experiment design needed to be corrected:

> "Can you use a line graph to show the effect of slow speed?"
>
> "Can you use a line graph to show the effect of irregular gait?"
>
> "Can you combine those two graphs into one picture?"

After several trials and errors, the "combined" graph was finally drawn by the students as shown in Figure 5, and the missing condition "slow speed and irregular gait" was added to the experiment design. Note that Figure 5 is in effect a figure of interaction in a 2x2 factorial design, a fairly advanced topic that appears in a typical statistics textbook for undergraduate students. Students could have been better prepared if they have taken statistics in a conventional classroom. Nevertheless, we felt it is important for the students to learn the knowledge acquiring strategies through PBL, rather than merely content learning.

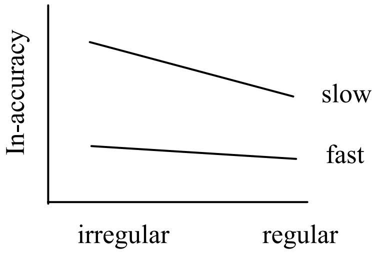

Figure 5. Experiment prediction by line graphs

It is noteworthy that this "graphically thinking" technique has benefited the students more than once on the same problem. The similar figures were used several times in later discussion. Without any further help from the facilitator, students have learned to utilize this figure in identifying an extra variable during the stage of data analyses. That is, they first noticed some "outliers" that were inconsistent with the main trend of the data, and most of these data points were collected from female subjects. They then decided to plot the interaction for male and female subjects separately, and they obtained two very different figures (the one for the female subjects showed significant interaction and the one for the male subjects did not). Recalling that they have observed more "hip-swings" on female subjects, they speculated that gender, or the related "hip-swing" might be another factor that affects the pedometer accuracy. Given the limited time and the large scale of the problem, and the minimal involvement of the facilitators, we believe that this is a strong piece of evidence that the PBL learning has indeed occurred effectively through model-based reasoning.

Improving MBR through PBL

Finally, we hypothesize that the benefits of learning model-based reasoning in the content-specific problems of our PBL classes might carry over to developing MBR as a general thinking strategy. We attempted to develop more quantitative evidence to show the correlations between MBR and PBL by comparing students' learning and problem-solving capabilities at different time intervals. For this purpose, we developed a questionnaire to survey the PBL class at both of the beginning and the end of the class, to assess whether and to what extent PBL might have facilitated the acquiring of model-based reasoning abilities. This line of study is still at its preliminary stage. In the following, we only briefly discuss some of the issues.

The questionnaire was developed to reflect the multiple dimensions of model-based reasoning, based on Grosslight et al. (1999) and Cartier, Rudolph, & Stewart (2001) (see the introduction section). The most important consideration was the particular nature of the PBL environment and our goal of evaluating the situatedness of model-based reasoning. Thus, we used a cover story in which a researcher was to solve a problem through a series of steps, such as literature search, generating hypotheses, drawing diagrams, building prototypes, and conducting simulations and experiments. Students were asked to identify the modeling techniques that were essential to problem solving. Out of total 64 students being surveyed, in the pretest, 31% of them reported that forming hypotheses was important at the beginning stage of research and in the post-test, 51% percent of them made the same identification (increased by 20%). Consequently, as to whether it is important to re-evaluate the hypothesis through experiments, 11% and 30% responded in the pre-test and post-test, respectively (increased by 19%). We reason that these changes in numbers reflected the changes in students' perception of modeling techniques in problem-solving, and particularly in this case, about the importance of hypothesis and its evaluation. This kind of change is consistent with the practices of the facilitators we have observed.

However, we believe that recognizing instances of MBR does not necessarily translate into being able to effectively solve problems using model-based reasoning. Whereas the assessment by survey may provide quantitative evidence on the students' general perception of model-based reasoning, to assess the actual usages of certain modeling skills, such as hypothesis formulation, graphical thinking requires relying more on the qualitative data collected from the real learning environment.

Conclusion

Model-based reasoning is a process of constructing representations in the form of a model (e.g., physical models, mathematical models) and deriving inferences through manipulation of the model, which requires a set of desired knowledge acquiring skills. The continuous observations over PBL classroom activities (group discussions, white board activities, and project presentations) provide us with unique insights into students' capabilities and learning processes in situated model-based reasoning in real world problem solving. By unpacking the dynamics of problem-based learning and identifying the links that demand model-based reasoning among different sub-components in the problem-solving process, one would be able to plan specific instructional moves that would strengthen such links and speed up problem-based learning.

Acknowledgements

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