Using "First Principles of Instruction" to Design Mathematics Flipped Classroom for Underperforming Students

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Abstract—**Although the use of Flipped Classroom has become increasingly popular among many educators, there is a pressing need to study how it is designed, implemented, and evaluated in actual practice. Moreover, there is scarcity of research on using Flipped Classroom as a remedial strategy in secondary school Mathematics education. The present article reports a study that explores the use of Merrill's First Principle of Instruction as an overarching framework to guide the design of Flipped Classroom. Kolb's Experiential Learning Theory is the main theory that informed the design of the learning activities. The Flipped Classroom learning environment was provided for 13 Form 6 (Grade 12) students who were underperforming in Mathematics. We examined the efficacy of the Flipped Classroom approach by using students' pre-post-test scores, student interviews, and teacher interview. Results of a paired *t*-test suggested a significant improvement in the students' post-test scores. While student perceptions of Flipped Classroom were generally positive, several suggestions for future design and implementation of Flipped Classroom are proposed based on the students' and teacher's suggestions.**

Index Terms—**flipped classroom, first principles of instruction, experiential learning theory, mathematics, underperforming students**

I. Introduction

Flipped Classroom is an instructional approach which has gradually become increasingly popular among many educators around the world [1]. In a typical Flipped Classroom setup, teachers prepare some instructional videos to introduce some basic materials so that students can learn them before lesson. In-class time is thus freed up for peer-supported learning activities, teacher feedback, and solving advanced problems.

Flipped Classroom appears to be a plausible approach to cater to underperforming students [2]. For example, students can pause or review the lecture videos repeatedly at their own pace. Also, by shifting part of the course outside the classroom, teachers can have more time to provide students with one-to-one assistance or small-group tutoring [3].

However, little empirical data have been collected regarding the use of Flipped Classroom in catering to diverse learners [2]. Furthermore, although a growing number of empirical studies have been conducted to investigate Flipped Classroom, very few were evidence-based or grounded their designs on relevant conceptual frameworks [4].

In the present study, we employed Merrill's First Principles of Instruction [5] as an overarching framework to guide the design of a Mathematics Flipped Classroom. Kolb's Experiential Learning Theory [6] is the main theory that informed the design of Mathematics learning activities, specifically coordinate geometry. By articulating our rationale of the design and the experiences gained, the present study provides guidelines for the design and implementation of Flipped Classroom, and would be helpful for future practitioners who seek a rigorous design framework to develop Flipped Classroom.

II. The Design of Flipped Classroom

This session first reviews what we have known about Flipped Classroom. Relevant theories and empirical findings were drawn to support our design. We then move on to discuss how we employed Merrill's First Principles of Instruction [5] to guide the design of Flipped Classroom. To enhance the teaching and learning of Mathematics, we incorporated Kolb's Experiential Learning Theory [6] when preparing the learning activities.

A. Flipped Classroom

Bishop and Verleger defined Flipped Classroom as an instructional strategy that consists of two parts, namely direct computer-based individual instruction outside the classroom, and interactive group learning activities inside the classroom [1].

Before class, students access the online learning materials which usually are instructional videos prepared by their teacher. Empirical findings suggested breaking a lesson into learner-paced parts [7], and limiting the duration of each instructional video within six minutes since it is the median engagement time of watching instructional videos [8]. For the video style, capturing instructor's drawing on a digital tablet is recommended since the natural motion of human handwriting can be

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more engaging than static computer-generated texts [9]. Furthermore, Mayer's Cognitive Theory of multimedia learning proposes various design principles that can facilitate student learning through multimedia instruction [7]. In fact, Morgan et al. utilized Mayer's theory to guide their video production of Flipped Classroom, and their students' comments showed a positive attitude toward the instructional videos [10]. Table I summarizes three major design principles that informed our video production. Fig. 1 shows a screen-shot of our instructional video (translated and transcribed in English for reporting purpose) and indicates the design principle applied.

TABLE I. SUMMARY OF THREE MAJOR MULTIMEDIA DESIGN PRINCIPLES APPLIED IN THE PRESENT STUDY

Design principles	Description
Segmenting	Break lesson into learner-paced parts: Limit the duration of each instructional video within six minutes
Signaling	Highlight essential material: Call learners' attention by underlining or spotlighting the key concepts
Personalization	Put words in conversational style: Use "I" and "you" as in an informal conversation with learners

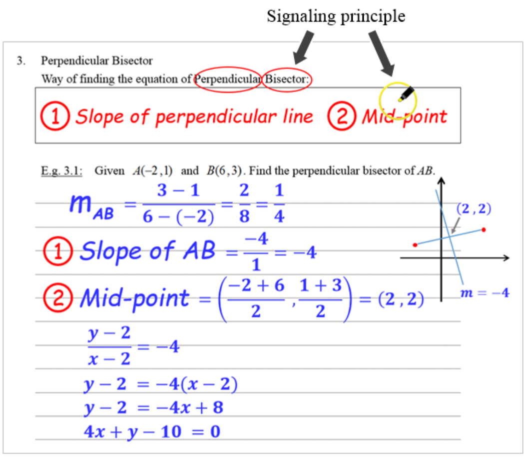

Figure 1. Screen-shot of a digital tablet drawing video style

Apart from the video lectures, in-class collaborative learning experience is one of the key success factors of Flipped Classroom [1]. In a social constructivist perspective, through the peer interactions such as discussion and collaborative problem solving, students' knowledge can be generated, elaborated, and revised [11]. In his Mathematics Flipped Classroom, Clark observed that more in-class time could be utilized for students to learn from each other by discussing problems, explaining procedures, and confirming answers [12]. In this regard, teachers should provide various learning problems which are suitable for group activities such as questions involving more advanced investigation, questions involving complex or difficult knowledge, and questions that can be answered in different ways [13]. For example, the question shown in Fig. 1 was considered as difficult for our students since various concepts and skills were required when solving the problem. Moreover, this question can be approached in different ways. Fig. 2 shows an alternative solution (English version) of the question. This is the PowerPoint slide that the teacher had prepared and planned to discuss in class.

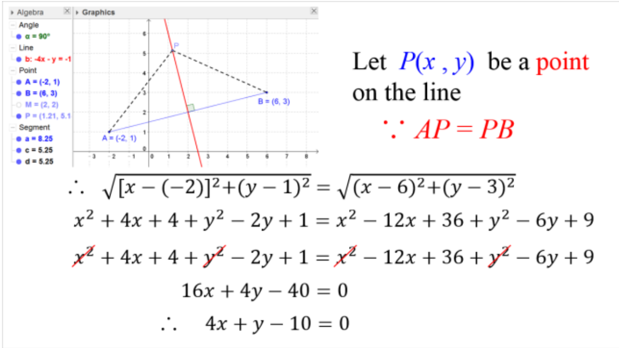

Figure 2. Alternative solution of the question shown in Fig. 1

B. *Merrill's First Principles of Instruction*

Merrill identified a set of principles which is commonly found in many instructional design theories and models [5]. Fig. 3 shows the conceptual framework of the First Principles of Instruction. Merrill stated that learning is promoted when:

Learners are engaged in solving real-world problems (Problem-centered);

- Existing knowledge is activated as a foundation for new knowledge (Activation);
- New knowledge is demonstrated to the learner (Demonstration);
- New knowledge is applied by the learner (Application); and
- New knowledge is integrated into the learner's world (Integration).

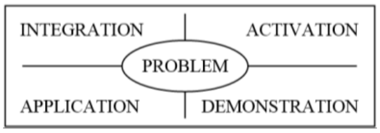

Figure 3. Conceptual framework of Merrill'S first principles of instruction [5]

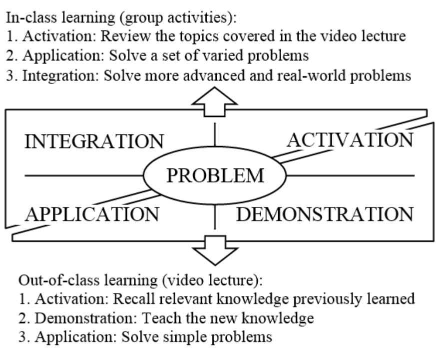

Figure 4. Overarching framework of designing flipped classroom

According to Merrill, learning is enhanced in direct proportion to the implementation of the First Principles, and this set of principles can be implemented in any education contexts. Studies done by other researchers (e.g., [14]-[16]) confirmed that the First Principles of Instruction can improve students' motivation and learning when compared with other forms of instruction. Based on Merrill's model, Fig. 4 shows our overarching framework of designing Flipped Classroom.

We delivered the activation, demonstration, and application phase of Merrill's model outside the classroom. In fact, students can go through these phases independently by visiting the video lectures. First, teachers can upload some revision materials (e.g., notes and revision videos) that are relevant to the learning of new knowledge. Students can thus activate the prerequisite knowledge by reviewing the materials if necessary. Second, teachers can use instructional videos to demonstrate the new knowledge and worked examples. Students can watch the instructional videos repeatedly so that they can learn at their own pace [12]. Third, a five to 10 minutes online follow-up exercise can be assigned [17]. Solving the problems in the exercise provides a chance for students to apply the new knowledge. At the same time, teachers can check students' mastery of learning by analyzing their responses. Based on the learning analytics, teachers can clarify any misunderstandings when returning to the classroom, or even adjust their teaching plan in response to students' performances [18].

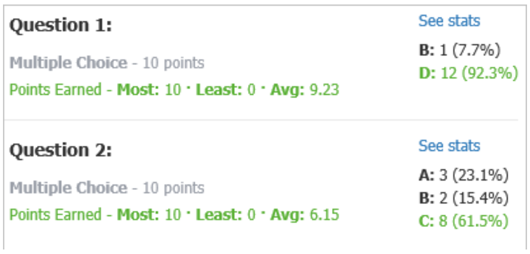

Figure 5. Learning analytics of an online exercise

In the present study, we employed an online course management platform (Schoology) to organize and deliver the out-of-class learning resources. And more importantly, the platform provided the teacher with learning analytics function of the students' online work. For example, Fig. 5 shows that only 61.5% of students answered Question 2 correctly. The teacher may consider discussing this question during the following face-to-face lesson.

For the in-class learning component, we conducted the activation, application, and integration phases of Merrill's model. First, teachers can prepare their students at the beginning of class by highlighting the key concepts learned in the video lecture [19]. It is especially important for the underperforming students since they may require additional guidance. Teachers can allow students to discuss the online questions that most of the students failed to manage, or provide simple group work to serve as a refresher of learning [20]. In their Mathematics Flipped Classroom, Kirvan, Rakes, and Zamora would first use one to three questions to activate and assess students' out-of-class learning [21]. In order to evaluate their answers within a short time, we utilized an application (Plickers) to collect students' real-time in-class responses. For example, Fig. 6 shows that all students had answered the two pre-lesson questions correctly. Teacher can thus proceed to the more advanced learning tasks.

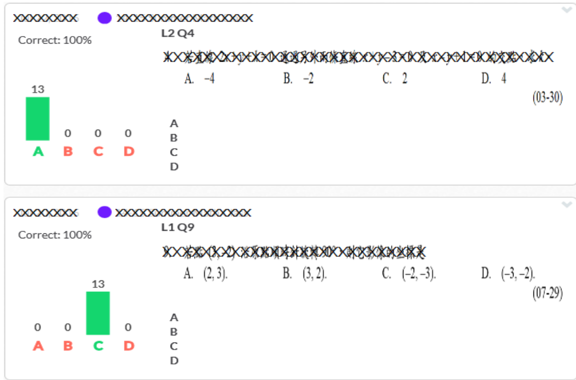

Figure 6. Learning analytics of students' in-class responses

For the application and integration phases, Merrill stressed the importance of students solving the advanced learning problems and real-world problems to reinforce their learning [5]. However, it may be difficult for the underperforming students to handle these tasks individually. So it is advisable to solve the advanced problems collaboratively in pairs or in groups [22]. In their Flipped Classroom, Warter-Perez and Dong found that group discussion could deepen students' understanding and help them integrate the new knowledge into real-world contexts [23]. Furthermore, teachers should circulate among groups to support student learning when necessary [24].

C. *Kolb's Experiential Learning Theory*

How can we design the learning activities of Flipped Classroom? Kolb considered experience as the foundation of learning [6]. Kolb's Experiential Learning Theory defines learning as the process of grasping and transforming experience into knowledge. As Fig. 7 shows, Kolb modeled the learning process as a four-staged cycle which comprised of concrete experience, reflective observation, abstract conceptualization, and active experimentation. The learning process is described as an idealized learning cycle if the learner goes through all the four stages.

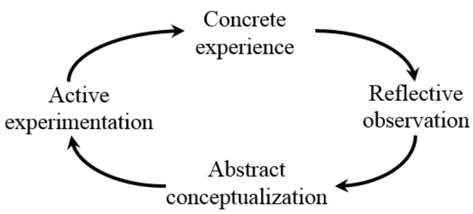

Figure 7. Kolb's experiential learning cycle [6]

According to Kolb [6], the learner must be able to:

- Involve themselves fully, openly, and without bias in new experiences (Concrete experience);
- Reflect on and observe their experiences from many perspectives (Reflective observation);
- Create concepts that integrate their observations into logically sound theories (Abstract conceptualization); and

- Use these theories to make decisions and solve problems (Active experimentation).

Very few empirical studies have hitherto focused on incorporating the Experiential Learning Theory in the contexts of Flipped Classroom. We found an article by Abdulwahed and Nagy that applied Kolb's model to design their laboratory education, where each hands-on lab session was paired with a pre-lab session [25]. Their pre-lab session employed a virtual lab setting which utilized computer simulations to visualize the experimental rig and show the experimental plots. They found that using the virtual lab helped students reflect more deeply on their experiences, and improved students' conceptual understanding during the hands-on session.

In the teaching and learning of geometry, visualization is the first level of geometric thinking, and accurate concept images are required in order to attain higher levels of geometric thinking [26]. Dynamic geometry software (e.g., GeoGebra) allows students to draw and manipulate figures accurately and easily. Students are thus able to observe the geometric properties and relationships through the dynamic courseware developed [27]. It can create an experimental environment to explore Mathematical concepts [28]. Then teachers can become a facilitator to assist students in constructing knowledge from their experiences [29].

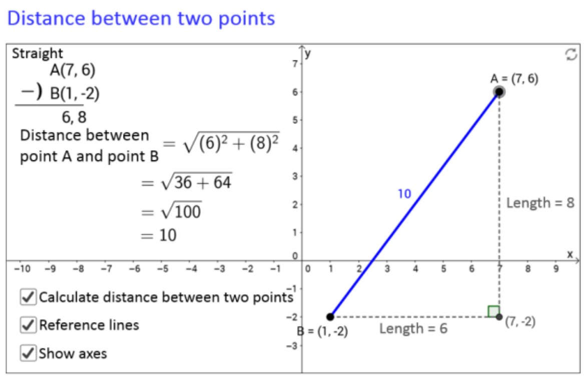

Figure 8. Screen-shot of a dynamic courseware (Distance between two points) [30]

TABLE II. SUMMARY OF KOLB'S LEARNING STAGES IN THE PRESENT STUDY

Learning stage	Activities
Concrete experience (pre-class)	Students manipulated the dynamic courseware (developed by GeoGebra) as a pre-lesson activity
Reflective observation (pre-class)	Students observed the geometric properties and relationships, and complete online exercises
Abstract conceptualization (pre-class)	Manipulating the dynamic courseware helped students develop their own individual initial concepts about geometric properties
Abstract conceptualization (in-class)	Teachers helped review and discuss the concept of geometric properties. Students' initial misunderstandings were corrected
Active experimentation (in-class)	Students applied the new concepts to solve problems with support from the teacher and peers when necessary

Table II describes the learning activities in each learning stage of Kolb's model and Fig. 8 shows one of the dynamic courseware (translated in English for reporting purpose) used in our present study. Students can manipulate the figure by moving point A and point B to observe the change of the distance between two points immediately. The calculation involved will also adjust accordingly.

III. METHODS

The objectives of this study were twofold: To test the application of Merrill's model [5] in the context of Flipped Classroom, and to examine the efficacy of the Flipped Classroom as a remedial strategy in Mathematics education. We thus addressed the following research questions:

- To what extent does the use of Flipped Classroom have an impact on underperforming students' Mathematics learning?
- What are the students' and teacher's perceptions of using Flipped Classroom?
- How can the design of Flipped Classroom be improved?

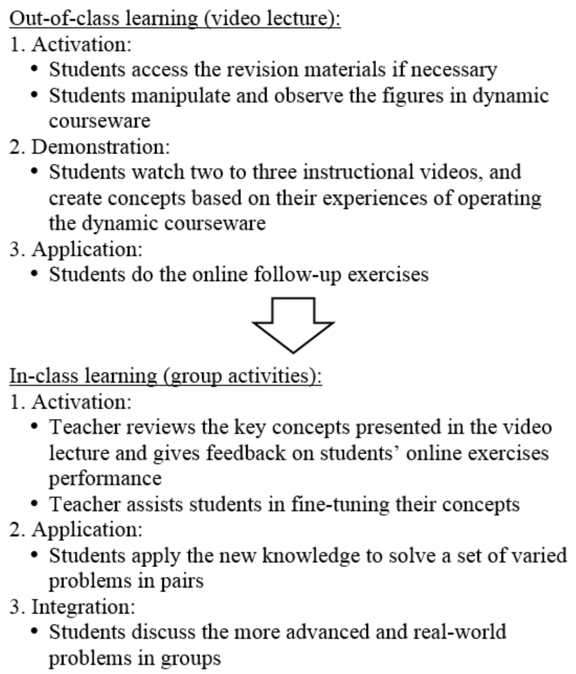

Figure 9. The flow of teaching and learning in each unit

A. *Participants and Setting*

Participants were 13 Form 6 (Grade 12) students from a Secondary school in Hong Kong. They were invited to participate in this project because of their underachieving performance in coordinate geometry. Before this study, they had minimal experience on Flipped Classroom. The end goal of the course was to solve the advanced and real-world problems related to coordinate geometry. Three consecutive units were designed. Each unit consisted of a video lecture and a 50-minute face-to-face lesson. In each video lecture, we provided a set of dynamic courseware concerning the geometric concepts presented, and two to three instructional videos with a duration within six minutes. Several online multiple choice questions were assigned after each instructional video. Paired with the video lecture, the face-to-face lesson echoed the out-of-class learning by first reviewing the key concepts delivered outside the classroom. Students were then divided into groups of four to five, and discussed some advanced and real-world problems. Fig. 9 shows the flow of teaching and learning activities in each unit.

B. Data Sources and Analysis

We drew data from three major sources in the present study, including pre-post-test scores, student interviews, and teacher interview.

First, 15-minute pre-test and 15-minute post-test were conducted to assess students' learning progress. The questions in pre-test and post-test were different but similar in terms of scope and difficulty level. Both of the tests included two questions and each question consisted of two parts. The first part of each question assessed students' basic knowledge on coordinate geometry, and the second part required students to demonstrate their ability of solving advanced problems. The total score of each test was 10, and thus the possible score range was 0 to 10. To analyze if there was any difference in the students' pre-post-test scores, a paired *t*-test was run. Since the qualitative work of student learning is important to evaluate Flipped Classroom [4], students' test scripts were also analyzed to investigate their understandings of concepts.

Second, semi-structured interviews of students and teacher were conducted to reveal their perceptions and experience of using Flipped Classroom. An interview protocol was designed and used in a consistent manner for each participant. The interview questions focused on three main themes: (1) Participants' overall attitude; (2) Benefits and challenges; and (3) Suggestions for improvement. Interview data was coded to identify themes and categories [31].

C. Validity and Reliability

To enhance the reliability and validity of our data, the following measures were taken:

- All test questions were adopted and modified from the public examinations in Hong Kong, which were officially designed by the Examination Authority;
- Emerging insights were related to the existing literature; and
- Member checking of the interview data [32], and direct quotations from participants in reporting the interview findings [33] were used.

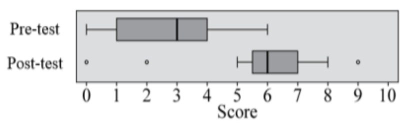

Figure 10. Box plot of the pre-test and post-test results

IV. Results

Fig. 10 shows the box plot of the pre-test and post-test results, and Table III compares the scores of the two tests. In a paired *t*-test, results indicated that the observed difference between pre-test and post-test was significant ($t(12) = 6.50$, $p < .0001$).

TABLE III. Comparison of the Pre-Test and Post-Test Scores

	Pre-test	Post-test	*t*-test
Mean (SD)	2.77 (1.79)	5.85 (2.41)	$t(12) = 6.50, p < .0001$

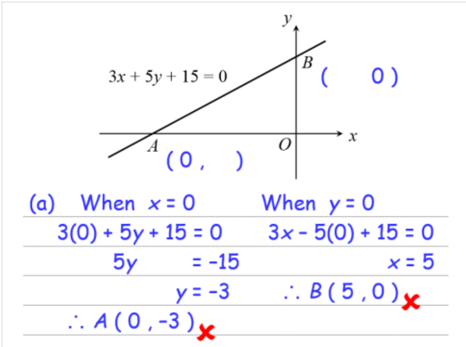

Figure 11. Student 1's working steps of finding the coordinates of A and B in the post-test

Still two students (Student 1 and Student 2) failed to manage most of the questions in the post-test. Yet we found that their concepts had improved to a certain extent when looking at their test scripts. Fig. 11 shows Student 1's working steps in the post-test, which reflected her confusion between x and y coordinates (translated and transcribed in English for reporting purpose). Indeed she did not score on this type of questions in both pre-test and post-test. But instead of leaving the question blank like what she did in the pre-test, she had compiled several steps which, although were incorrect, showed her willingness to attempt answering the question. In the words of her teacher, "It is a good start for an underperforming student."

Student 2 also did not perform well in pre-test and post-test. But affectively, he enjoyed the Flipped Classroom since more in-class time was spent on peer interaction and, in his words, "my classmate can answer my questions immediately when I don't understand."

For the student interviews, the interview data was thematically analyzed and organized into three categories: (1) Course content and design; (2) Collaboration with peers; and (3) Teacher's supports. Table IV summarizes the coding categories of the interview data, along with some representative students' quotes.

TABLE IV. Summary of the Coding Categories of Student Interviews

Category	Examples
Course content and design	"I have moved the points on the webpage (dynamic courseware), and calculated the slope many times." "The final problem (real-life problem) is very difficult. … I need to do more exercises. In this way, I can master the skills better."
Collaboration with peers	"Learning in groups is better since my classmate can answer my questions immediately when I don't understand."
Teacher's supports	"We cannot ask question immediately while watching video."

As for the teacher interview, we identified two major benefits of using Merrill's First Principles of Instruction in designing Flipped Classroom, and incorporating Kolb's Experiential Learning Theory in teaching coordinate geometry.

- First Principles of Instruction: "The First Principles of Instruction design theory offers me explicit guidance in designing my flipped classroom approach. I observe that my out-of-class learning activities should focus on the demonstration of new knowledge, while the in-class learning activities focus on handling more advance problems in a peer-supported learning environment."
- Experiential Learning Theory: "Every student can access individually the dynamic courseware at home, which is not quite feasible in a normal classroom. Their experiences of manipulating the geometric objects provide students with a solid foundation of learning."

We also identified two main challenges of using Flipped Classroom, especially for the underperforming students:

- "In the Flipped Classroom model, students have to solve the advanced or real-world problems to promote their learning. But practically, some students may find it difficult to solve these problems."
- "While more in-class time can be spent on one-to-one support, some students in need of help have to wait for a long period of time when I am occupied with other students."

V. Discussion

The results are discussed in two main sections: Impact on underperforming students' Mathematics learning, and students' and teacher's perceptions of using Flipped Classroom. Several suggestions for the design and implementation of Flipped Classroom are proposed.

A. Impact on Underperforming Students' Mathematics Learning

From the pre-test and post-test results, there was a significant learning gain ($t(12) = 6.50$, $p < .0001$). Thus we might assume that the use of Flipped Classroom was useful in increasing the Mathematics achievement of underperforming students.

But in the present study, some students still underachieved after the intervention. Yet when comparing their working steps in the pre-test and post-test, students' concepts and skills had improved to a certain extent. For example, a few students initially did nothing in the pre-test. It turned out that they could demonstrate some understandings in the post-test, although their knowledge may not be perfectly demonstrated. In fact, the teacher argued that "It is a good start for an underperforming student."

This confirmed the necessity of researchers qualitatively analyzing students' work when evaluating the efficacy of Flipped Classroom [4]. Especially for the underperforming students, their improvement may not be fully reflected in the score of our standard tests. Thus by analyzing their working steps, we could gather more information about students' learning in Flipped Classroom.

B. Students' and Teacher's Perceptions 0f Using Flipped Classroom

With the framework of Merrill's First Principles of Instruction [5], the way of designing Flipped Classroom is clear instead of relying on a teacher's intuitive belief. The teacher reported that direct demonstration of new knowledge and doing simple online exercises were suitable for out-of-class learning, since students could complete these learning tasks on their own. For the in-class learning, the teacher observed the peer-supporting behavior among students such as exchanging ideas and explaining concepts to others. Most of the students were thus able to handle the advanced learning problems collaboratively. Indeed, their test results confirmed an improvement in their learning.

From the student interviews, most of the students reported that Flipped Classroom facilitated their learning. In their out-of-class learning experience, various students pointed out that they could pause the video clip when they could not follow teacher's presentation. In this way, they would have enough time to think about the material or take notes. As highlighted by the following student, "In the usual classroom teaching, I have no time to think. But if I watch videos, I can stop it for a moment when I don't understand." In fact, some students may feel embarrassing to interrupt their teacher during the lecture even though they cannot follow the lecture. But in Flipped Classroom, watching the instructional videos makes it possible for every student to learn at their own pace [2].

However, some students commented that "We cannot ask question immediately while watching video." In other words, students in the present study could not receive instant help during the video lecture. Similar comments were reported in Wanner and Palmer's Flipped Classroom [34]. A discussion forum should thus be provided for students and teacher to communicate with each other. Teachers may also arrange virtual office hours to hold live online chats with students who seek help.

As for the teaching of coordinate geometry, the teacher affirmed that using dynamic courseware as a pre-lesson task facilitated student learning: "Their experiences of manipulating the geometric objects provide students with a solid foundation of learning." In addition, normal classrooms often have insufficient computers for every student. By delivering the dynamic courseware outside the classroom, "Every student can access individually the dynamic courseware at home." In the present study, students had made use of the dynamic courseware to assist their learning. As a student mentioned, "I have moved the points on the webpage (dynamic courseware), and calculated the slope many times."

In the face-to-face lesson, students liked learning in groups and solving the advanced problems collaboratively. Their preferences echoed Clark's findings [12]. However, we would remark that the advanced learning tasks should be used with caution especially for the underperforming students. The teacher stated that "some students may find it difficult to solve these problems." In fact, a few students reflected that "The final problem (real-life problem) is very difficult. … I need to do more exercises. In this way, I can master the skills better." Therefore, we suggested providing more exercises concerning the application phase of Merrill's model. Consequently, the students can have a better preparation for handling the more advanced or real-world problems.

Last but not least, the teacher mentioned a situation in his Flipped Classroom: "While more in-class time can be spent on one-to-one support, some students in need of help have to wait for a long period of time when I am occupied with other students." In fact, this problem was also reported in Enfield's Flipped Classroom [35]. So how can we address the needs of students when the teacher is temporarily not available to help?

We suggest adopting peer instruction for Flipped Classroom. As Abeysekera and Dawson hypothesized, peer instruction fits within the contexts of Flipped Classroom based on the body of research to support its efficacy [4]. In the present study, a student pointed out that "Learning in groups is better since my classmate can answer my questions immediately when I don't understand." Consistent with Topping and Ehly's comments on peer-assisted learning [36], the one who offers help would also benefit. In the words of a student, "When helping others, I find that I can have a better understanding." Similarly, in their Mathematics Flipped Classroom, Love, Hodge, Grandgenett, and Swift found that explaining a problem or idea to classmates could help students develop a deeper understanding of concepts [18].

However, the peer instruction activities in the present study can be arranged in a more organized way. For example, Crouch and Mazur outlined a possible arrangement of peer instruction [37], which is summarized as follows:

Lesson is divided into a series of short session, each focused on a learning item and followed by a related question;

- Students are given a few minutes to formulate individual answer and report to the teacher;
- Students then discuss their work with groupmates and try to convince or assist each other by explaining their answer;
- The teacher circulates among groups, listen to their discussion, and provide feedback; and
- Finally, the teacher checks whether the correct answer can be reached after the discussion, and then explains the question if necessary.

In fact, Crouch and Mazur remarked that in order to free up class time for problem solving and discussion, the students should complete some teacher-assigned tasks before class [37]. Therefore, their suggestion may be suitable for the contexts of Flipped Classroom. However, the evidence of integrating peer instruction into Flipped Classroom is still scarce, and further research is required [4].

VI. Conclusion

In this paper, we describe our experience of applying Merrill's First Principles of Instruction [5] to design a Flipped Classroom learning environment for underperforming students in Mathematics. We also incorporated Kolb's Experiential Learning Theory [6] into the design of our learning tasks. We found that this learning approach significantly improved the students' post-test scores, and that students' perceptions toward Flipped Classroom had been positive. Nevertheless, we cannot over generalize these results. We suggest adopting peer instruction for the future study of Flipped Classroom. Further research involving other student participants is also needed to examine the effects comprehensively.

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