WORK IN PROGRESS: A Computer-Aided Design Intelligent Tutoring System Teaching Strategic Flexibility

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Abstract

Taking a Computer-Aided Design (CAD) class is a prerequisite for Mechanical Engineering freshmen at many universities, including at Washington State University. The traditional way to learn CAD software is to follow examples and exercises in a textbook. However, using written instruction is not always effective because textbooks usually support single strategy to construct a model. Missing even one detail may cause the student to become stuck, potentially leading to frustration.

To make the learning process easier and more interesting, we designed and implemented an intelligent tutorial system for an open source CAD program, FreeCAD, for the sake of teaching students some basic CAD skills (such as Boolean operations) to construct complex objects from multiple simple shapes. Instead of teaching a single method to construct a model, the program first automatically learns all possible ways to construct a model and then can teach the student to draw the 3D model in multiple ways. Previous research efforts have shown that learning multiple potential solutions can encourage students to develop the tools they need to solve new problems.

This study compares textbook learning with learning from two variants of our intelligent tutoring system. The textbook approach is considered the baseline. In the first tutorial variant, subjects were given minimal guidance and were asked to construct a model in multiple ways. Subjects in the second tutorial group were given two guided solutions to constructing a model and then asked to demonstrate the third solution when constructing the same model. Rather than directly providing instructions, participants in the second tutorial group were expected to independently explore and were only provided feedback when the program determined he/she had deviated too far from a potential solution. The three groups are compared by measuring the time needed to 1) successfully construct the same model in a testing phase, 2) use multiple methods to construct the same model in a testing phase, and 3) construct a novel model.

Introduction

Computer-Aided-Design (CAD) software development was started by General Motors Research Laboratories in the early 1960s. Today, CAD software has become the most prevalent engineering design approach used in industry. Traditional engineering drafting approaches use pencil and ruler, and a design transform requires erasing and redrawing. CAD software translates the problem into changing model parameters so that design modifications become much quicker. Other advantages of CAD software are the zoom in and zoom out features, which simulate a camera lens so designers can inspect details of elements of an assembly as well as evaluate the shape of an assembly as a whole. Three-dimensional (3D) solid models are able to rotate on any axis so designers could have a full understanding of the object.

Mastery of CAD software has become necessary for mechanical engineering students and civil engineering students. In Washington State University, taking a CAD class is a prerequisite for Mechanical Engineering freshmen. However, a majority of universities often find it difficult to devote a significant amount of time to CAD instruction in the curriculum [1]. Universities usually employ CAD software tutorials in their engineering graphic lab period to teach solid modeling skills and CAD software functions and features. There are numerous tutorials available for popular CAD software, which can be summarized into three types:

1) Tutorials published by the vendor

2) Tutorials published by professionals

3) Personal tutorials published on video websites

Most CAD software vendors have tutorials on their websites: Solidworks published static guidance of basic mechanical parts as well as videos on the website [2]and the AutoCAD research team published embedded tutorials [3] based on gamification theory to encourage learning. CAD software vendors tutorials are primarily skill-based and emphasize introducing software functions and features [4]. Learners will be given a goal model, which will usually be a common mechanical part, such as screw nuts or shells, and then the tutorial will instruct the user to construct the given model step-by-step with CAD software tools. Tutorials published by professionals are usually more advanced and are in a textbook-like format [5]. Advanced tutorials focus on refining solid modeling skills and are often more complex than those of software vendors. They demonstrate excellent modeling skills by providing several similar exercises and helping the learner become familiar with these skills. The third type of tutorial is the pre-recorded process of solid model construction, some of which also have oral instruction. Publishers of this type of tutorial include individuals, online education communities, and some are CAD vendors. One can say that the traditional way of CAD software learning is a one-way teaching style, in which students are required to follow every step of the tutorial materials and have to examine mistakes carefully by themselves there is no interaction between students and the tutorial material.

Intelligent tutoring systems (ITSs) form a special category of educational technologies. They simulate human tutor behaviors of guiding students in solving given problems and collaboratively assisting students through adjusting while solving the problem. ITSs can directly focus on the problem that the student is working on, leading the student to understand exactly when they make a mistake. ITSs are beginning to be widely used in the US, as with Cognitive Tutors, which

are grounded in cognitive theory and cognitive modeling. These intelligent teaching tools are employed in mathematics instruction in roughly 2700 schools. Evaluation studies also show that ITSs enhance learning compared to more typical forms of instruction [6].

Learning to use CAD software involves developing declarative and strategic knowledge such as selection of solid modeling alternatives and use of modeling constraints [1]. Strategic knowledge [7] is concerned with knowledge of the alternate methods by which a specific task may be achieved and the process by which a choice may be made. Teaching students using a single method to construct a solid model, in fact, does not target learner's "designing ingenuity" but is limited to the memorization of design procedures of ready-to-use objects and templates [8]. Chester [7] discussed the importance of strategic knowledge in teaching CAD software, the paper concludes that the employment of strategic knowledge early in the modeling process may prevent later model failure. The effectiveness of comparing alternative solutions in mathematics instruction has been discussed in prior efforts [9, 10, 11]. Results of these investigation studies indicate that students instructed by comparing alternative solutions can learn more than those instructed by the single solution. Osakue [12] published an instructional method on teaching solid modeling skills with AutoCAD. The method proposes that, at a planning stage, decomposing complex solid models into segments and sketching each segment isometrically helps students learn the extrusion operation concept of CAD software, as well as Boolean operations. The feedback from students shows breaking down complex solids into segments helps students understand solid modeling principles and such principles will be helpful in the use of other CAD software. However, there are few ITSs that are developed to teach students solid modeling skills. There are also few empirical studies in the literature on ITSs that relate to the effectiveness of teaching multiple strategies [6].

In this paper, we discuss an intelligent tutorial system for an open sourced CAD program, FreeCAD. The tutorial system employs strategic flexibility in the tutoring process. The distinction between our work and previous research efforts in ITSs lie in solution adaptive. ITS systems that have been published are capable of adjusting the students from wrong steps to the right one, however, they support only single solution for each problem, any solving sequences that are distinct from the pre-determined solution will be considered as incorrect. Our system, on the other way, encourages learners to apply multiple solutions for each problem.

Hypothesis

The research is motivated by our desire to explore novel instruction methods for basic solid modeling skills in CAD software, as well as to evaluate the effectiveness of employing strategic flexibility in CAD sketch skills. It aims to validate three hypotheses:

1) Teaching multiple strategies with an ITS is more effective than a textbook

2) Content taught by textbooks should be easy for students to follow but may not be helpful in solving new problems

3) Combining guidance and practice is more effective than only using a textbook or following an exercise step-by-step

Method

In our preliminary experiment, we will test three teaching approaches: 1) *exploration mode*, in which participants have to figure out three strategies by themselves; 2) *textbook mode*, in which participants will follow three strategies from a textbook; and 3) *partial guidance mode*, in which participants will be instructed to perform two strategies at the beginning and then are requested to figure out a third solution.

Each group will have four post-tests. The first and the second post-test require the participant sketch previous models, using two different methods. The purpose of the two tests is to validate hypotheses 1 and 2. The third post-test asks participants to construct a new model. The fourth post-test is optional and its purpose is to both challenge the student and to make the experiment more interesting. The purpose of the third and fourth post-tests is to validate hypothesis 3.

FreeCAD Intelligent Tutoring System

The FreeCAD intelligent tutorial system aims to teach basic CAD skills. In this paper, we focus on the skill, namely Boolean operation (union, intersect and subtract), which is necessary for understanding solid modeling principles [12]. We the tutorial system for a parametric 3D modeler, FreeCAD, that allows solid models to be modified by changing parameters [13]. The tutorial system can present three different instruction approaches, which are described in method section.

The reason for choosing FreeCAD is because of it highly customizable, scriptable and extensible; FreeCAD allows developers to build their own interfaces as well as functional components. The tutorial system is built within workbench, a customized user interface. The program is developed in Python 2.7 and we build all basic primitives for users with python-based scripts. Learners are not required to build basic objects by themselves, which allowing them to focus on learning principles of solid modeling. To trace all learners' operations, we built go back and restart functions. Boolean operation functions are imported from FreeCAD library. For each goal 3D model, we applied a search and planning algorithm, an AI approach, to compute all possible construction sequences under certain constraints.

The tutorial system consists of five components: introduction, pre-test, training, post-test, and post-survey. A flow chart of the tutorial process is shown in Figure 1.

At the project introduction stage, the tutorial briefly introduces the overall tutorial process and user interface. Participants will be required to enter age, major and group number. There are three groups that correlate to the three instructional methods. Figure 2 shows an overview of the user interface of the tutorial system, Figure 3 shows the detail on the top, Figure 4a shows the detail of the right-hand side components in the interface. Learners can select primitives, Boolean operations and task submission from the top. On the right-hand-side, there is a task description, a goal model, and available options. A timer is embedded at the bottom on right-hand-side, which begins countdown when the task starts. The center area is where the solid model will be constructed. FreeCAD supports navigation of solid models through rotation view [14],which is a general function available for most CAD software, and the tutorial has a reminder in the interface to help learners learn this skill.
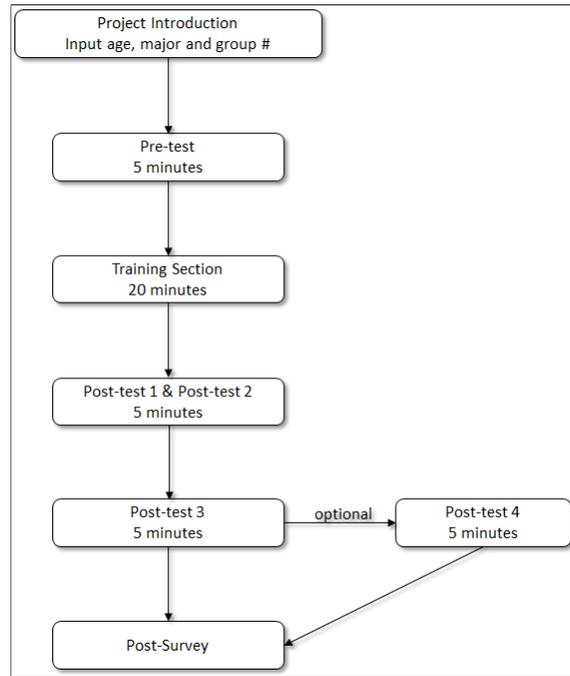
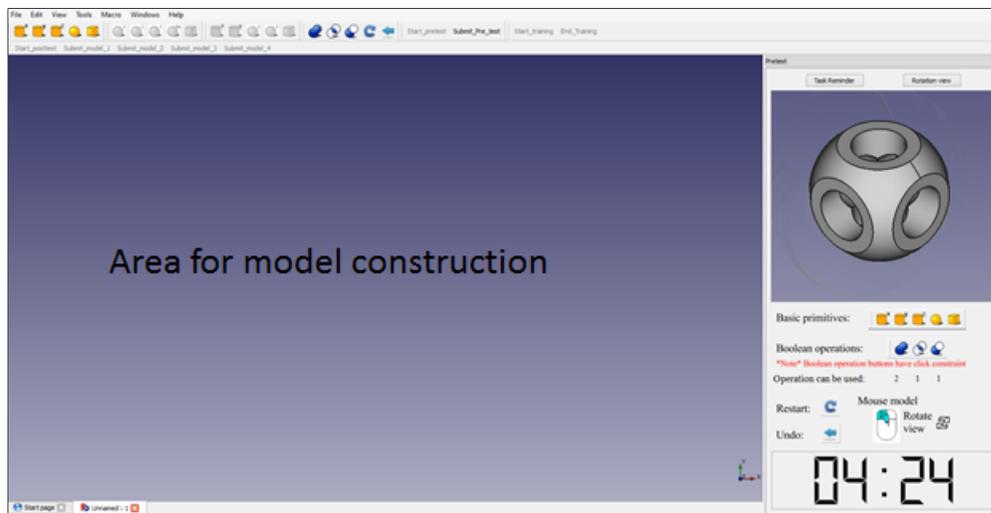Figure 1: Flow Chart of FreeCAD Intelligent Tutorial System
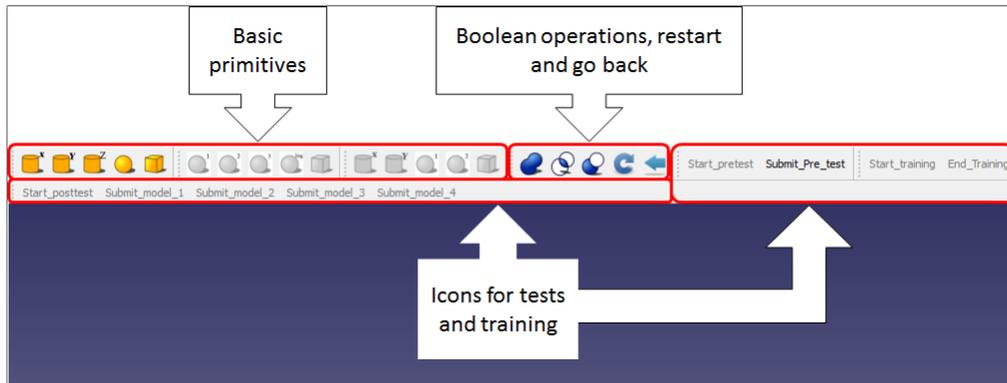

Figure 2: An overall view of user interface

Figure 3: Details on the top of the user interface
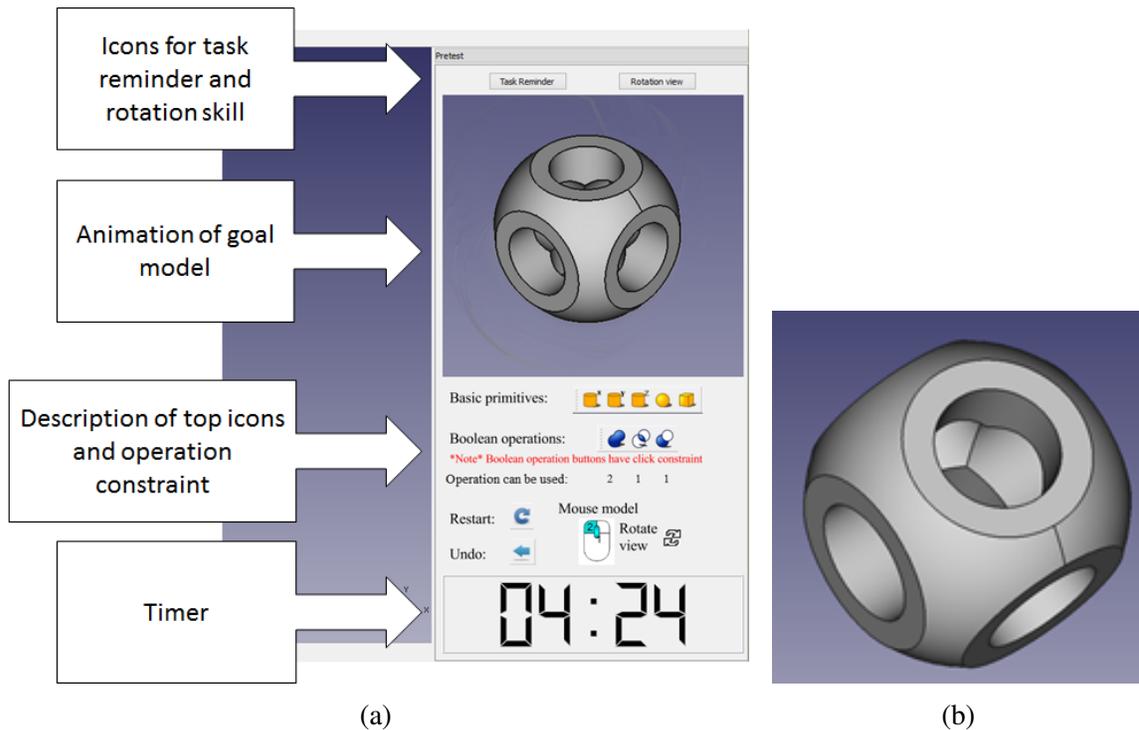

(a)

(b)

Figure 4: (a) Details of the right-hand side of the user interface. (b) Goal model for pre-test, training section and post-test 1 and 2

During the pre-test, the learner will be given five minutes to construct a given model, shown in Figure 4b. The solid model is a famous one that can be constructed from primitives by a constructed solid geometry (CSG) tree. Nevertheless, there is no research has done before to construct this model by using multiple ways of Boolean operations. Under the constraints of using four operations (1 intersect, 1 subtract and 2 unions) and five primitives (3 cylinders, 1 sphere, and 1 cube), our planning algorithm computed more than one hundred methods that can construct the CSG model successfully. We expected that most participants would be unable to solve the pre-test successfully if they had no prior CAD experience.

The content of the training section for each group is different. Group 2 is the textbook mode and is considered to be the control group. Learners in group 2 will be given a textbook we made to teach three methods to construct the model. We choose three fundamental distinct solutions allowing the learner to compare them during the training. A demonstration of the three methods is shown in Figure 5, the static description of their sequences is shown in Table 1. An example of the textbook is shown in Figure 6, which demonstrates a sequence of Boolean operations to the learner: union the three cylinders first (step 1 to step 4, Figure 6a) and then subtract the union from the sphere (step 5 to step 7, Figure 6b), and then intersect the cube with the common part from last Boolean operation (step 8 to step 9, Figure 6c).
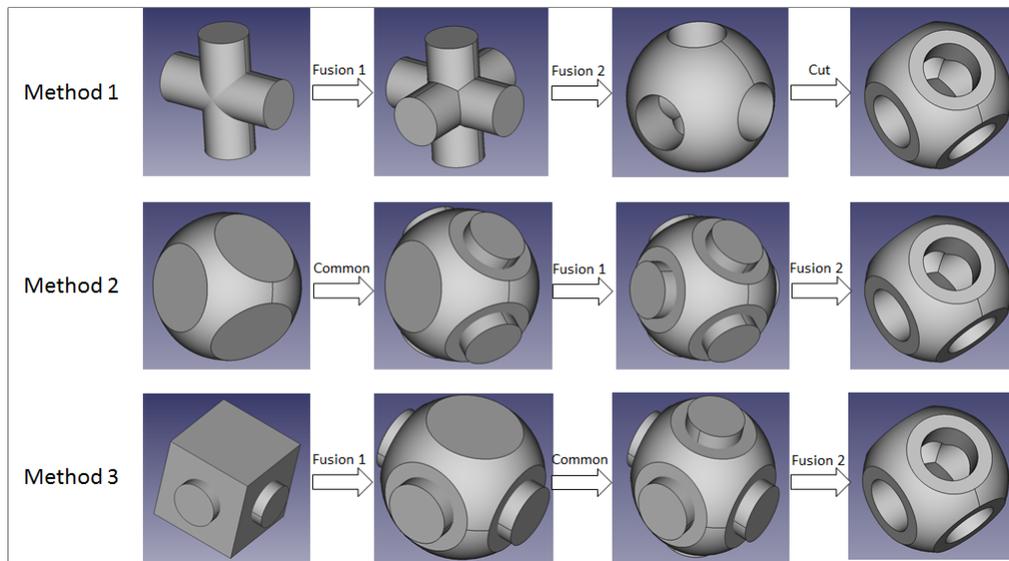

Figure 5: Three methods that employed in the textbook

Group 1 and Group 3 are exploration mode and partial guidance mode, respectively, and their training is guided by the tutorial system. An example of the user interface is shown in Figure 7. It consists of three components at the right-hand-side of the screen. The top is a comprehensive icon introduction for the tutorial, which shows a primitive's name and a Boolean operation's name. The suggestion window is located under the icon instruction.
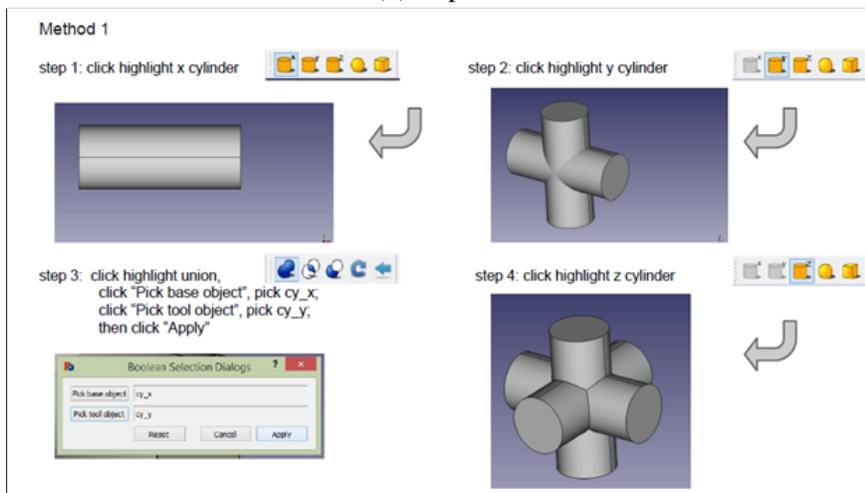
The content of the suggestion window depends on the subject group and the selected Boolean operation. The training section of group 1 is in exploration mode; the suggestion window will not give any guidance at the beginning but will encourage learners to try whatever he/she think is
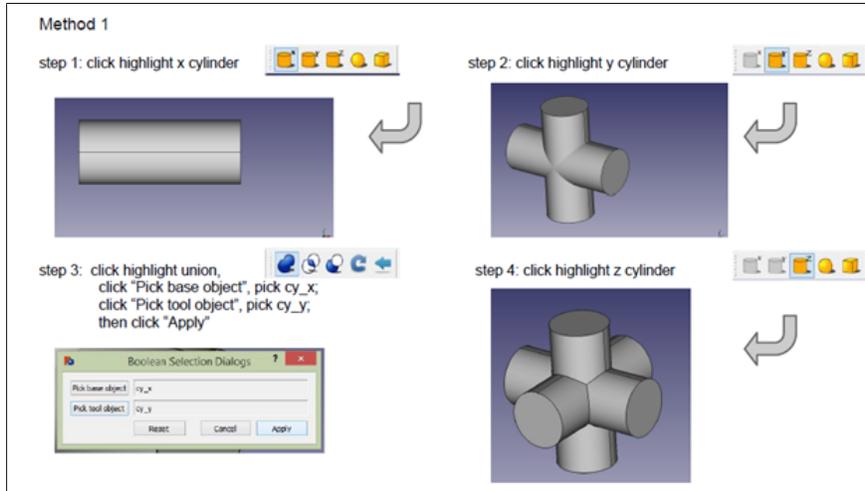
(a) step 1-4
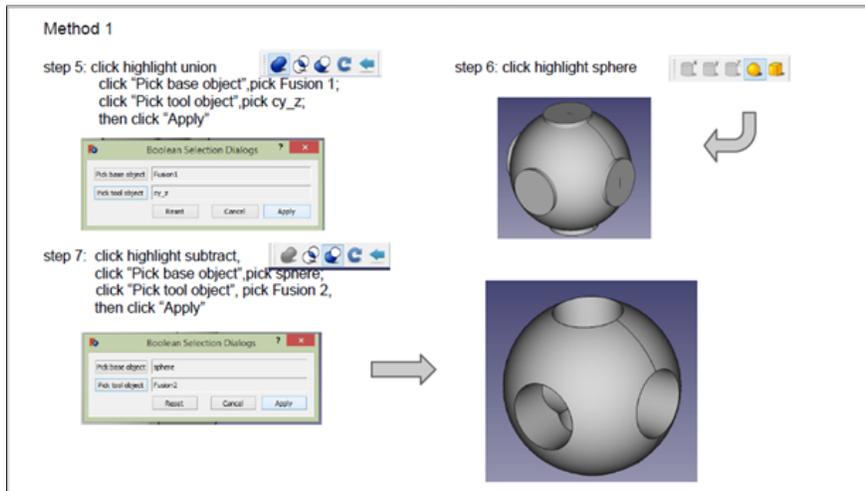
(b) step 5-7

(c) step 8-9

Figure 6: Example of a method to construct solid model using FreeCAD tutorial

Table 1: Three methods instructed in textbook

| Method #	Step	Boolean Operation	Primitive 1	Primitive 2	Result
	1	Union	cylinder x	cylinder 1	fusion 1
	2	Union	fusion 1	cylinder z	fusion 2
Method 1	3	Subtract	sphere	fusion 2	cut
	4	Intersect	cut	cube	goal model
	1	Intersect	cube	sphere	common
	2	Union	cylinder x	cylinder 1	fusion 1
Method 2	3	Union	fusion 1	cylinder z	fusion 2
	4	Subtract	common	fusion 2	goal model
	1	Union	cylinder x	cylinder 1	fusion 1
	2	Intersect	cube	sphere	common
Method 3	3	Union	fusion 1	cylinder z	fusion 2
	4	Subtract	common	fusion 2	goal model
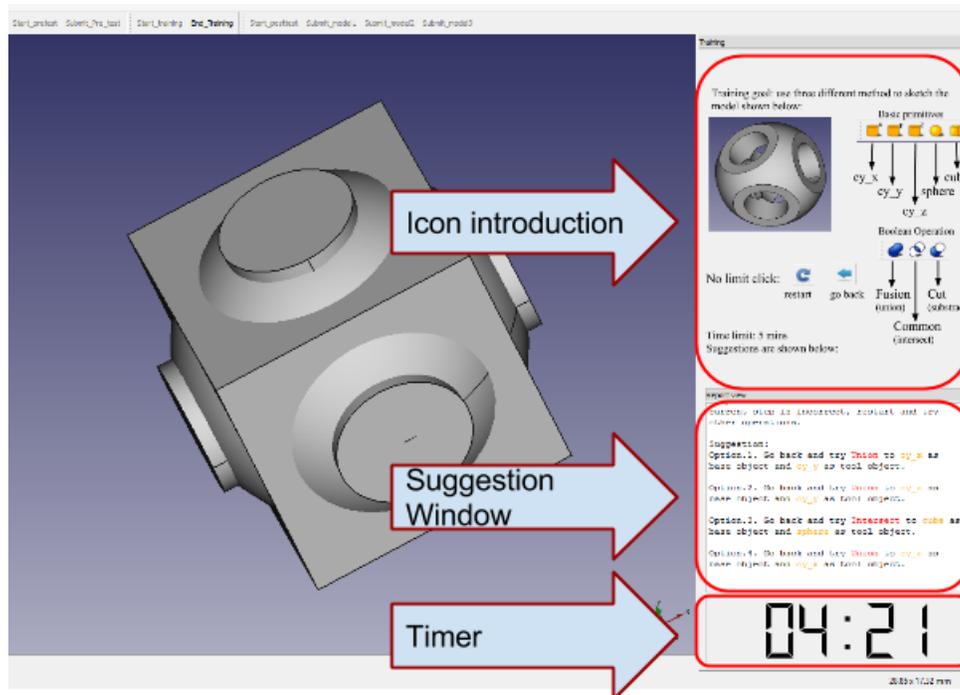
Figure 7: User interface of training section in group 1 and group 3

correct. When an incorrect operation is made, the tutorial will give advice regarding the correct operation. The training section of group 3 is in partial guidance mode; the suggestion window demonstrates a complete operation sequence to construct the goal model. The first two sequences are exactly as same as method 1 and method 2 of the textbook. When it finds the learner has finished the steps shown in the suggestion window, it will give another operation sequence to construct the same model. Once the learner finishes the two methods, he/she will be asked to figure out a new method to construct the same model. Figure 8 shows a static guidance given at a group 3 training section.

The tutorial system knows all possible operation sequence paths to achieve the goal. In the training section, if it finds that the present step deviates from the correct path, it will give all possible paths that direct to the right direction. For example, an incorrect step shown in Figure 9; the learner has subtracted a cylinder from the sphere, which is incorrect. The tutorial will warn that the present step is incorrect and will offer 2 possible ways for the step. Figure 9 shows the incorrect step and suggestions from the tutorial.

For all three groups, the training section lasts at most 20 minutes. Once the learner constructs the solid model in three different ways he/she can end this section. A timer is embedded at the bottom at right-hand-side. The timer begins countdown when the section starts.

Post-test 1 and post-test 2 requires the learner to construct the solid models that have practiced in the training section, but the learner has to use two different sequences of steps. The two tests must be finished within five minutes, they serve as review tests for the contents that had been instructed in the training section.

The task in post-test 3 is to construct a new model with only four steps (1 intersect, 1 subtract and 2 unions) and five primitives (4 spheres and 1 cube). The model is shown in Figure 10a. It can be constructed using Boolean operation sequences similar to those in the training section. This task serves as question test to check the learner's mastery of solid modeling skills. Demonstrating a single solution sequence is sufficient to pass the test.

Post-test 4 is optional and was added as a more difficult challenge. The goal model of this test is shown in Figure 10b. To pass this test, learners need to use a Boolean operation sequence with four steps (1 union, 1 subtract, 2 intersect) and five primitives (2 spheres, 1 cube, and 1 cylinder). We employed the same AI algorithm to compute all possible solutions, from which we obtained more than 300 sequences to successfully construct the model.

Preliminary Results

We carried out an experiment of FreeCAD tutorial, which has been approved by institutional review board (IRB), and recruited 14 students by means of campus advertisement. The 14 students were from a variety of majors: 4 are in Mechanical Engineering, 5 are in Civil Engineering, 2 are in Computer Science, 1 is from Chemistry, 1 is from Education Psychology and 1 is from Material Science. Each student has been rewarded $15 as compensation. They had been randomly divided into three groups. There are four in group 1, five in group 2 and five in group 3. All collected data are stored anonymously. The duration of the experiment is approximately 45 minutes.

Percentages of students who successfully passed tests are shown in Figure 11 (i.e., those partic-

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step 1 Please add cy_x.
step 2 Please add cy_y.
step 3 Union to cy_x as base object and
cy_y as tool object.
step 4 Please add cy_z.
step 5 Union to Fusion1 as base object
and cy_z as tool object.
step 6 Please add sphere.
step 7 Subtract to sphere as base object
and Fusion2 as tool object.
step 8 Please add cube.
step 9 Intersect to Cut as base object
and cube as tool object.
```

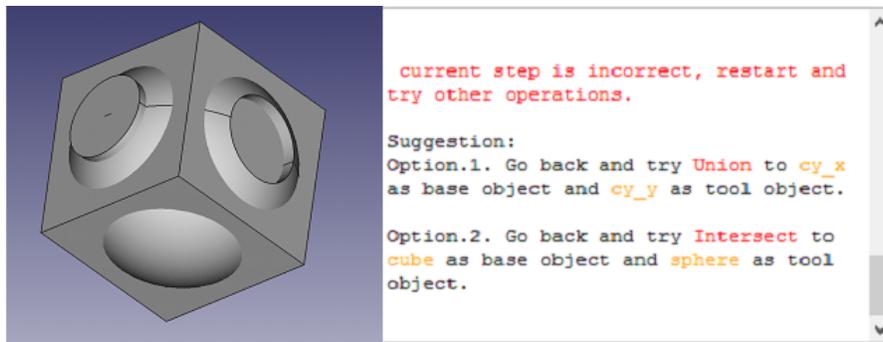Figure 8: An example of guidance to construct the goal model


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  current step is incorrect, restart and
try other operations.

Suggestion:
Option.1. Go back and try Union to cy_x
as base object and cy_y as tool object.

Option.2. Go back and try Intersect to
cube as base object and sphere as tool
object.
```

Figure 9: An example of tutorial suggests ways to alert the user after an incorrect step

(a)   (b)
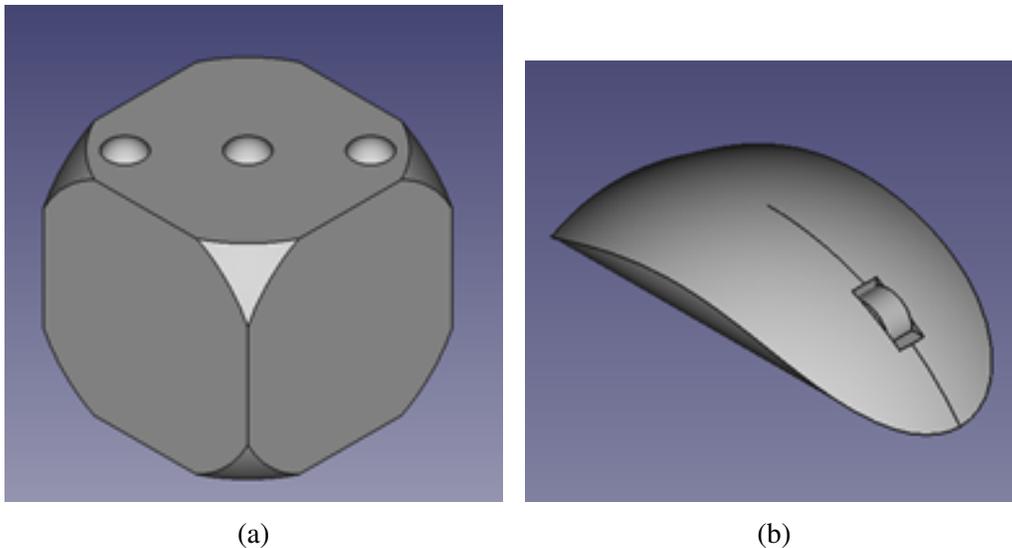
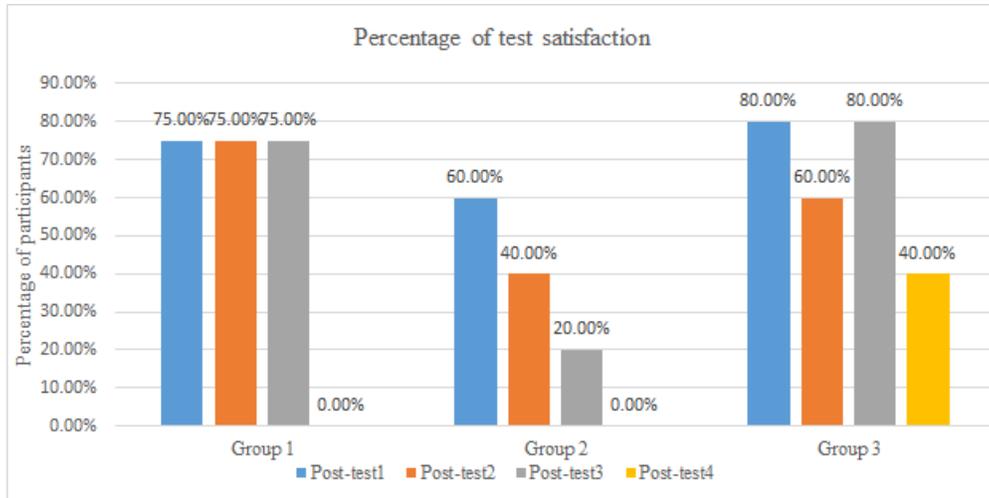Figure 10: Goal model for (a) pre-test 3 and (b) post-test 4.

Figure 11: Percentage of participants test satisfaction

ipants who could construct the goal model within the time limit). The pass rate of group 1 and group 3 are higher than group 2, indicating that using an ITS during training is more effective than following written instructions in the textbook mode.

Students who pass post-test 3 indicate they mastered the skill of using Boolean operations by constructing a model they were not explicitly trained on. Students who pass post-test 4 indicate an even higher level of understanding. The pass rate of post-test 3 in group 1 and group 3 are higher than in group 2. The pass rate of post-test 4 in group 3 is higher than in both group 1 and group 2, suggesting that a combination of guidance and practice is more effective in solving new problems than only using a textbook or guided exercises. Note that the guidance in the textbook was designed to have the same overall quality as the guidance given to group 3.

The average time spent on each section is shown in Figure 12. The length of time at each section indicates the difficulty of that section, which aims to validate our hypothesis 2. The training section of group 1 has the longest time and group 2 has the shortest. We compared the training operation log of group 2 and the methods of the textbook, students in group 2 followed all the steps of the textbook, which shows the length of time spent in the three training sections suggests that the textbook is easier (or at least faster) to follow than the intelligent tutorial. The textbook mode group has the lowest pass rates on post-test 3, suggesting that content taught by textbooks may be easy for students to follow but not be as helpful in solving new problems.

The post-survey is collected at the end of the experiment. It is a questionnaire asking participants about their usage experience. The questionnaire has 15 statements, Question 1 to Question 4 are about gender, previous experiences of CAD software and the level of interest in geometry math class, respectively. Table 2 lists the statement of Question 5 to Question 14 and the average rating of responses to the statements in the questionnaire is given in the last column. Because of the sample size limitation, the conventional statistical analysis is of limited value. Question 15 is about how comfortable the participant is with computers. Recruited students are requested to rate these statements with 1: strongly disagree, 2: disagree, 3: undecided, 4: agree, 5: strongly agree. 14 students responded to the questionnaire. The minimum average response is 2.86 (Question 10)
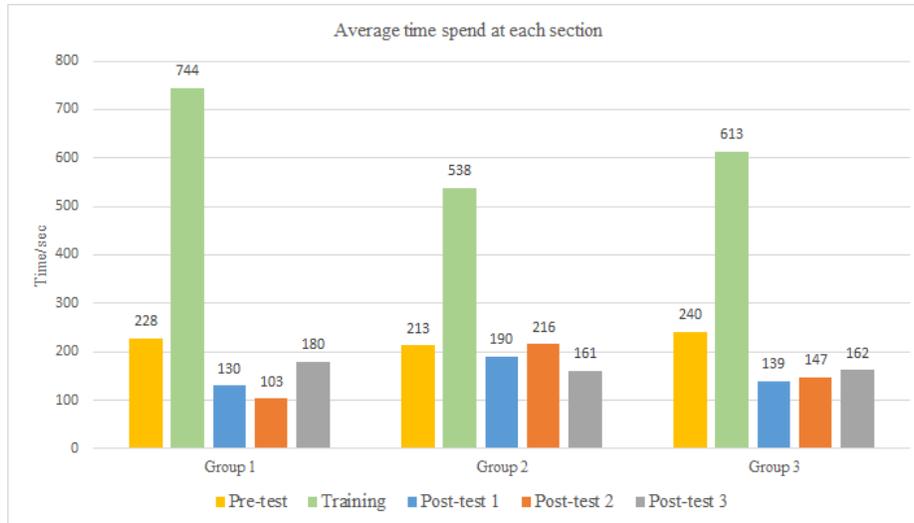
Figure 12: Average time spends at each section

and one may conclude that the students believe the pre-test model was not easy, which helps to explain why the average time spent on pre-test is higher than it spent on post-tests. The average response of Question 11 shows that students largely agree that after training the solid models, post-test 1 and post-test 2 are easy to pass. The maximum average response is 4.21 (Question 7), which deals with subjective feelings to instruction with multiple solutions. The average rating to this statement demonstrates that students believe teaching multiple solutions helps them to understand solid modeling construction principles. Based on the overall responses in Table 2, and data from our preliminary experiment, we believe that using our FreeCAD ITS holds promise.

Table 2: Post-survey on FreeCAD tutorial experience

Question #	Statement	Rating
5	Do you agree with the following statement: I enjoyed using this method to learn to sketch a CAD model.	3.79
6	Do you agree with the following statement: It makes completing sketching easier than I expected.	3.57
7	Do you agree with the following statement: Multiple solutions is an effective teaching method	4.21
8	Do you agree with the following statement: Completing training was not frustrating	3.71
9	Do you agree with the following statement: I did not have to work hard to complete training.	3.43
10	Do you agree with the following statement: The pre-test was easy.	2.86
11	Do you agree with the following statement: After training, making the first two objects was easy.	3.79
12	Do you agree with the following statement: After training, making the final (novel) object was easy.	3.00
13	Do you agree with the following statement: Learn multiple ways to construct the same object was easy.	3.86
14	Do you agree with the following statement: I understand Boolean Operations better than I did before.	3.86

Conclusion

We have assessed a novel instruction method to teach basic solid modeling skills for CAD software. The tutorial aims to teach Boolean operation (union, intersect and subtract) skills, employing multiple strategies as teaching method during instruction. We investigate three instruction methods: exploration mode, textbook mode, and partial guidance mode.

We carried out a preliminary experiment to validate our hypotheses with 14 participants. Results of our tests provide preliminary data indicating that using an ITS is more effective than using textbook (hypothesis 1), a combination of guidance and practice will be more effective in solving new problems than only use textbook or exercise (hypothesis 3), and the textbook is easier to follow than an ITS but is not as helpful in solving new problems (hypothesis 2).

The contribution of this research includes the following. First, we designed and implemented an intelligent tutoring system for the FreeCAD software system. Second, our ITS was able to automatically discover and demonstrate multiple solution methods for a single goal model. Third, we performed a preliminary evaluation of teaching effectiveness for three different ways of learning CAD software. Fourth, our results suggest that a combination of suggestions and guided exploration allow students to best apply their learned knowledge to novel tasks.

The primary limitation of this research is sample size: we expect to recruit more students to the experiments in the future. To enlarge the sample size, crowdsourcing would be an option to recruit a more diverse set of people to evaluate teaching effectiveness. Future work could also focus on improving the training section through a machine-learning algorithm that could discover the optimal time to interrupt a participant and to give explicit guidance towards the exact issue the participant is working on. An additional method to provide guidance to a participant could be via animation, rather than static text, as was suggested by some of the participants in this study. Finally, further study could develop techniques to automatically generate video demonstrations of all possible ways to construct a given model.

Acknowledgements

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