Should we teach free-body diagrams before or after Newton's Laws?

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Abstract. There are two interesting lesson sequences for teaching force and motion in high-school physics. These are teaching free-body diagrams before Newton's laws (FbN) and teaching Newton's laws before free-body diagrams (NbF). Both sequences were found in physics textbooks. Different authors adopted the sequence that they believe it would affect student understanding better. However, some physics experts did not agree with this. It is therefore interesting to know if we should teach with the FbN or NbF sequence. This motivates us to study the effect of such lesson sequences on student understanding of force and motion. The sample group was grade-10 students from two physics courses in 2020. One course was taught with the FbN sequence (29 students) and the other with the NbF sequence (34 students). Their understanding was evaluated by using an assessment test which consisted of three parts including (1) Newtonian concept, (2) problem solving, and (3) free-body diagrams. The result shows that for the Newtonian concept part, the average scores are 11% for the FbN and 13% for the NbF sequence. The average scores of the problem-solving part are 13% and 9% and those of the free-body diagram part are 41% and 48% for the FbN and NbF sequences, respectively. The scores of all parts between the two sequences were not significantly different. In addition, student difficulties found in all parts were similar. However, a larger number of students who could provide the equation of motion ($F = ma$) in the problem-solving part was found in the FbN sequence. We might conclude that teaching free-body diagrams before or after Newton's laws did not affect student understanding in the topic of force and motion. Detail of student difficulties in both sequences will be further discussed.

1. Introduction

Many teachers tried to develop their teaching approaches to help students understand what they learn. They also arranged the contents in the sequence that might help students. According to Driver (1994), a well-planned curriculum can help students understand the subject. However, a curriculum is normally constructed based on the logical structure of the subject and not on students' background knowledge [1]. Moreover, the logical structure depends on individual's ideas. An example is shown in force and motion chapter in several well-known textbooks. There are two interesting structures (or lesson sequences) which are introducing free-body diagrams before Newton's laws (FbN sequence) and introducing Newton's laws before free-body diagrams (NbF sequence). The first sequence can be found in textbooks [2] and [3] while the other is shown in textbooks [4] and [5]. Therefore, the objective of this work is to study the effect of lesson sequences on student learning on the topic of force and motion.

2. Methodology
Two lesson sequences were developed and both included the same 4 subtopics which are Introduction of force, Newton's laws, Free-body diagrams and Problem solving. The only difference between the two sequences is the order of the 2nd and 3rd subtopics (see figure 1).

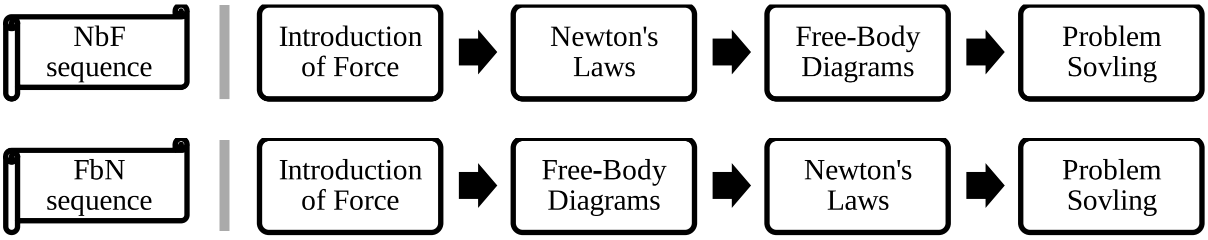

Figure 1. The NbF and FbN lesson sequences.

The lesson sequences were used in 2 high-school classes during the second semester of academic year 2020. One class used the FbN sequence (29 students) while the other used the NbF sequence (34 students). Although the two classes were instructed by different teachers, the researchers observed that both teachers instructed with a similar style. In addition, one teacher joined the other class to make sure that they would not make any difference other than the lesson sequences. Each subtopic was taught for 50 minutes except for the problem-solving subtopic when 100 minutes were spent.

The student knowledge was evaluated by using an assessment test. The test includes Newtonian concept, problem solving and free-body diagrams. The first part of the test was the force sled question set from the FMCE (Thai version) [6]. There are 7 situations in this part and the students must choose the condition that correctly explains each situation. The second part was a multiple-choice question translated from Rosengrant (2005). It asked for a magnitude of the friction force between a vertical pillar and a fireman who is moving down to the ground with a constant downward acceleration [7]. In this part, a blank area was provided in the test for students to write down their solving procedure. The last part consists of two questions to probe student understanding of free-body diagrams as shown in figure 2.

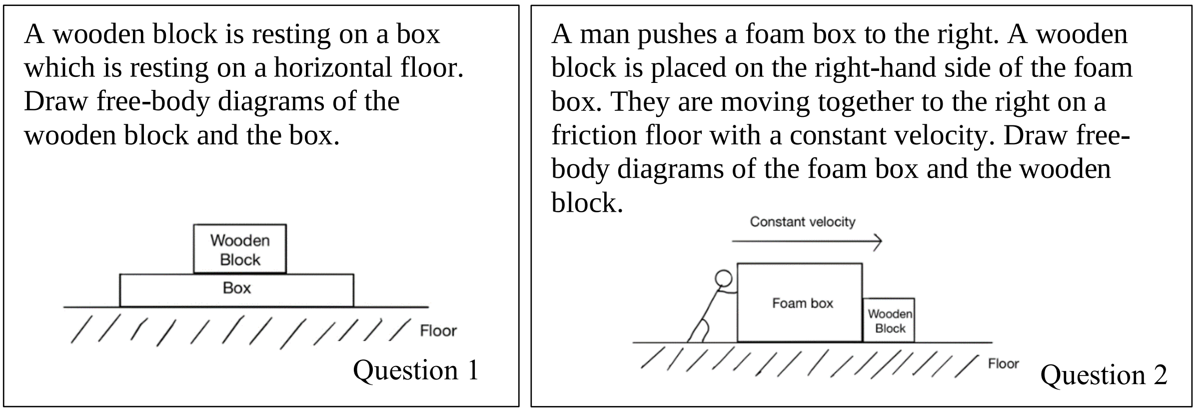

Figure 2. The questions in the free-body diagram part in the assessment test.

3. Results and discussion
The results from the assessment test were the same between the two groups. For the Newtonian concept part, the FbN students had the average score of 11% and the NbF of 13%. The data shows that the most popular answer for each situation is similar in both groups of students. They thought that the direction of motion defines the direction of force and a change of velocity magnitude is influenced by a change of the magnitude of force.

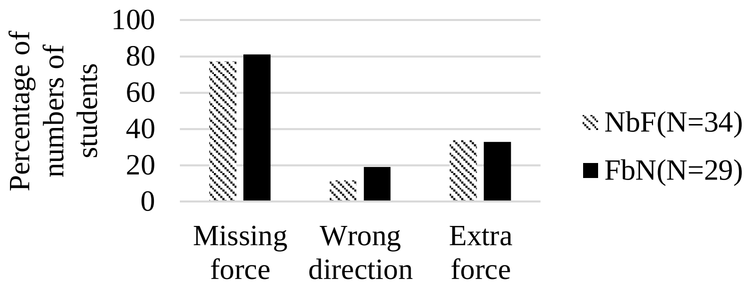

Figure 3. Numbers of students giving each category of mistakes in the free-body diagrams.

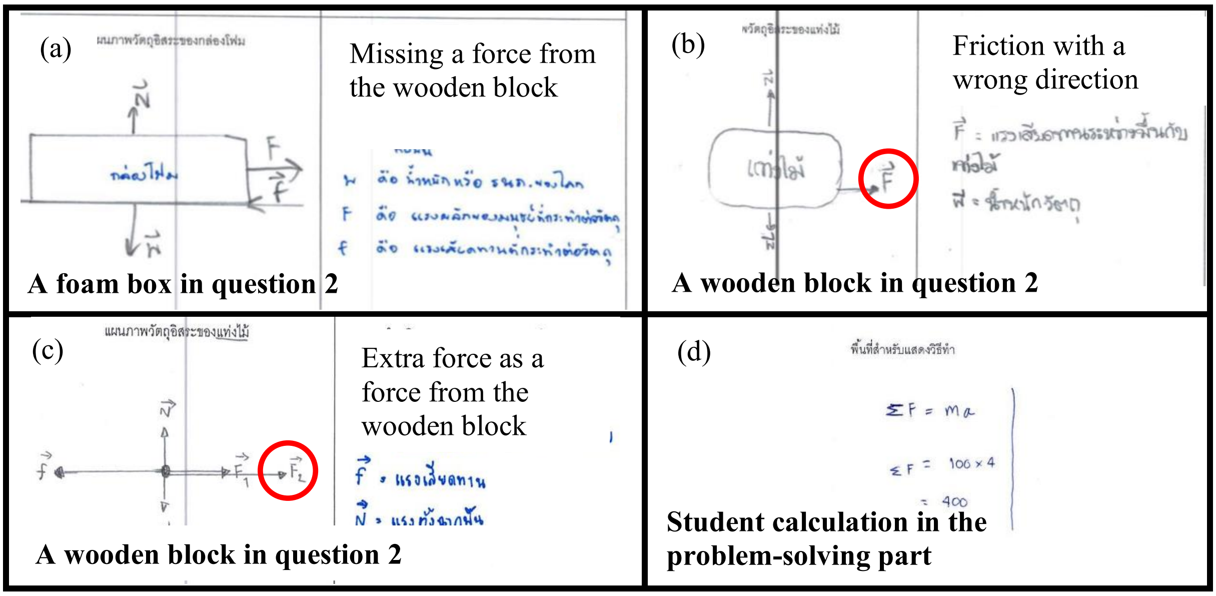

Figure 4. Examples of students' free-body diagrams (the second question): (a) missing a force from the wooden block (b) giving a wrong direction of friction force (c) giving an extra force in the free-body diagram of a wooden block, and (d) student calculation in the problem-solving part.

Next, for the problem-solving part, 13% and 9% of the students from the FbN and NbF sequences, respectively, could successfully find the correct answer. Finally, in the free-body diagram part, students from the FbN and NbF sequences provided average scores of 41% and 48%, respectively.

The mistakes in students' answers about free-body diagrams were categorized into three types. If some forces were missing in the free-body diagram, the data was collected as a "missing force" mistake. If the correct force was given but with a wrong direction, the data was collected as a "force with wrong direction" mistake. Finally, if there was an extra force which should not be involved in the free-body diagram, the data was collected as a "extra force" mistake. Figure 3 shows the percentage of students giving each mistake in their diagrams. The similar pattern of the results can be seen where the highest mistake found in both groups of students was the "missing force". Those missing forces are a force acted on the box by the wooden block in the first question and a force acted on the foam box by the wooden block in the second question (figure 4(a)). These mistakes of students from both sequences are the same. Figures 4(a) – 4(c) show examples of student drawing a free-body diagram in each category. For the "force with wrong direction" category, few students were confused about the direction of some forces such as a weight, a normal force and a friction force (figure 4(b)). For the "extra force" category, a few students thought that some forces should appear in the free-body diagram such as a friction force in question 1 and a force from the object itself (figure 4(c)).

The results from all three parts of the test seem to indicate that both groups of students gained similar knowledge after learning with different lesson sequences. However, an interesting point was found in the results from the problem-solving part. From the blank area provided in the assessment test for students to write down their calculations, it was discovered that students from the FbN sequence could realize that Newton's second law is the key to solve the problem. The evidence is that they wrote the equation $F = ma$ in the blank area as shown in figure 4(d) while most of the students from the other group did not write anything in the blank area.

4. Conclusion

The results from the assessment test which measure the knowledge of Newtonian concept, problem solving and free-body diagrams of the students from both sequences are significantly similar. This means that different lesson sequences did not affect student learning on force and motion. However, a larger number of students from the FbN sequence could realize about the use of the equation of motion in solving the problem. To improve the study, conducting the experiment with a larger sample group and improving the instruction for both sequences are suggested to confirm that lesson sequences cannot affect student learning.

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