ISSN 1303-0485 • eISSN 2148-7561
DOI 10.12738/estp.2015.3.2526
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Educational Sciences: Theory & Practice • 2015 June • 15(3) • 787-795

Received | 22 April 2014
Accepted | 19 March 2015
OnlineFirst | 14 April 2015

An Analysis of High School Students' Mental Models of Solid Friction in Physics

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Abstract

Students often have difficulties understanding abstract physics concepts, such as solid friction. This study examines high school students' mental models of solid friction through a case study of 215 high school students in the ninth through twelfth grades. An achievement test with three open-ended questions was created, with questions limited to descriptive and visual responses regarding the concept of solid friction. The gathered data were analyzed in terms of rubrics that were used in related literature. By using the rubrics, the various levels of understanding by students were determined separately by the two researchers. The percentage of case agreement between the researchers was calculated as 90% for description and 84% for visualization. The results showed that students mostly think about solid friction at the macroscopic level and have difficulties making sense of it at the microscopic level (i.e., students' mental models are not scientific). In the light of these results, it is recommended that instructors endeavor to explain solid friction at macroscopic, mesoscopic, and microscopic levels.

Keywords: Mental model • Solid-friction • High school students • Students' learning difficulties • Physics education

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Physics courses include many abstract concepts, such as force and energy, and students' difficulties in fully grasping these concepts are frequently discussed in related literature. It is hard for students who have incorrect or missing information about physics to correctly form new ideas (Clement, 1982). Determining students' preliminary information about target concepts and structuring courses accordingly is necessary for successful physics education (Dekkers & Thijs, 1998; Kurt & Akdeniz, 2004). Science educators must uncover students' preliminary information, especially about force concepts (as one of the cornerstone concept of physics) to aid understanding of more complex topics.

Many studies have investigated force and related concepts, and this practice can be classified into the following four types: (*a*) students' conceptions related to force concepts (Brown, 1989; Helm, 1980; Trumper & Gorsky, 1996, 1997); (*b*) students' conception levels of force concepts (Dekkers & Thijs, 1998; Halloun, 1998; Heywood & Parker, 2001; Jimenez-Valladares & Perales-Palacios, 2001); (*c*) alternative approaches to teaching and learning force (Besson, Borghi, De Ambrosis, & Mascheretti, 2007; Kurt & Akdeniz, 2004; Şahin, 2010); and (*d*) studies focusing on teaching specific types of force (Besson & Viennot, 2004). This study focuses on students' mental models about solid friction (i.e., friction between two solid bodies as opposed to drag).

Mental Models

Models are generated as the result of the simplification and reduction of a structure, demonstrating the relationship between objects in a system (Hestenes, 2006). Mental models are internal or cognitive presentations of a system (Bower & Morrow, 1990; Harrison & Treagust, 1996; Rapp, 2005), and they exhibit privatization by drawing attention to predictive and descriptive characteristics (Nersessian, 1992). An individual uses a mental model to explain, perceive, and understand real world behaviors and structures new mental models on existing frameworks within the personal context. In fact, mental models are related to perceptions acquired as a result of one's actions, and an external or conceptual model can be developed by generating codes about these perceptions (Hestenes, 2006). Accordingly, an individual's mental model may be revealed on the basis of expressions and actions that reflect perceptions about a given concept.

Because the learning process includes mental model structuring (Hanke, 2008; Hanke & Huber, 2010) and learning deficiencies or incorrect perceptions may occur due to inadequate learning environments, students' solid friction mental models need to be examined within the context of existing learning environments. According to Vosniadou (1994), knowledge about mental models will be instructive for teachers in understanding and accommodating difficulties.

Solid Friction and Students' Learning Difficulties

People benefit from friction on a daily basis without being aware of it, and understanding friction is essential to learning advanced physics concepts. However, friction is typically taught in a superficial, abstract way in standard physics courses (Besson et al., 2007), and is often perceived by students as a force arising from irregularity in surfaces or a reaction to movement (Nuhoğlu, 2008). Besson and Viennot (2004) stated that this misunderstanding is tied to mislearning Newton's third law. Many teaching methods have a negative effect on the formation of incorrect and non-scientific student perceptions related to solid friction in physics courses, as the generally adopted approach is based on examinations at the macroscopic or mesoscopic levels. A macroscopic example often provided shows a pushing force applied to an object, designating the existence of friction with an arrow pointing in the opposite direction, as seen in Figure 1a. This prompts students to interpret friction incorrectly as

Figure 1: Representations of friction force at a macroscopic level.

a reaction force against movement. In Figure 1b, the existence of friction force is examined fragmentally, yet students still have difficulties understanding friction force at the macroscopic level (Besson & Viennot, 2004).

The existence of friction is presented in more detail at the mesoscopic level (Figure 2a), promoting the structuring of more qualified perceptions (Besson and Viennot, 2004). However, investigating at the mesoscopic level limits the understanding of friction to a narrow context, as a force arising from irregularity in surfaces (Nuhoğlu, 2008). In Figure 2b, friction is presented at the microscopic level, outlining the interaction of object and surface molecules. Kurnaz (2011) examined the understanding of energy transfer at the macroscopic and microscopic levels and its effects on mental model development, and determined that the use of both levels facilitates understanding and development of scientific mental models. However, Kurnaz's results were limited to energy transfer on friction surfaces. In recent years, friction has begun to be presented in a more comprehensive way (Knight, 2008; Kurnaz, 2011). In this sense, there is a need to examine students' overall mental models about solid friction to increase teachers' ability to educate effectively.

Based on the above literature, this study investigates high school students' mental models about solid friction. The following research questions were used to identify answers within the scope of this study:

- How were student understanding levels about solid friction distributed in grades?
- How did student mental models about solid friction change according to grades?

Method

This case study used a qualitative perspective on mental models of student understanding about solid friction. This enabled examination of the target status in its own context (Yin, 2003).

Sample of Research

To obtain basic information about students' mental models related to solid friction, a wide range of participants were included: 57 ninth graders, 39 tenth graders, 63 eleventh graders, and 56 twelfth graders. These 215 participants were all located in a city in the Black Sea region of Turkey. The participants were selected through purposive sampling strategies from a general high school. Students in grades 9–12 were selected as the sample because these levels of Turkish students are exposed to more detailed information about solid friction than other regional high schools. Thus, to reflect the student mental models related to the research subject, criterion-based purposive sampling strategy was applied (e.g., all participants were required to have taken physics courses and to be in end of the term). According to national education programs, students are expected to understand reaction forces between a variety of friction surfaces. Friction force is classified as either static or kinetic and is analyzed in solid bodies and one dimension (Ministry of National Education [MoNE], 2011a). In textbooks prepared in accordance with the curriculum and as utilized in this study, solid friction is presented directly at the macroscopic level in the ninth grade (Kalyoncu, Tütüncü, Değermenci, Çakmak, & Bektaş, 2008) and indirectly at the microscopic level in eleventh and twelfth, via the concepts of internal energy and energy transfer (MoNE, 2011b, 2011c, 2012; Kurnaz et al., 2012).

Instrument and Procedures

In order to elicit the mental models of students, a data collection tool based on Hill (2010) and Kurnaz (2011) and including open-ended questions was used. Hill indicated three dimensions of

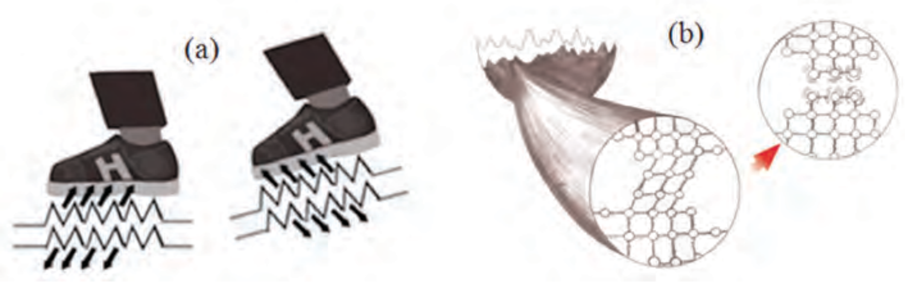
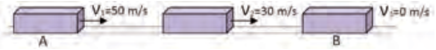


Figure 2: Examples of friction force at mesoscopic and microscopic levels.

information in a mental model: *content knowledge* concerning a subject, event, situation, process, or concept (identifying information related to modeled reality); *structure knowledge* (knowledge about the network of relationships); and *operational knowledge* (knowledge about a situation using content and structure specifics). Kurnaz indicated that questions aimed at theoretical and practical knowledge reveal mental models, and pointed out that operational knowledge reflects practical information about content while structural knowledge reflects theoretical concepts of the reality modeled. This study was limited to students' theoretical knowledge, which was assessed only through the following three questions:

1. What is friction? Explain.
2. Explain reasons for friction.
3. The object shown in the figure below is moving from position A to position B and rests on position B. Visualize the interaction(s) between the object and surface area molecules during this process.



Question types were limited to descriptive and visual answers related to solid friction and were prepared based on physics textbooks and curriculum. In addition, a physics education academician examined the questions in terms of understandability and practicability to increase validity and reliability. A pilot study was conducted with 30 high school students and results showed that questions were structured at a proper level of understandability and data additivity. During the data collection process, participants were given 30 minutes to respond to the questions.

Data Analysis

The method of matching understanding levels to rubrics in order to reveal students' mental models (İyibil, 2010; Sağlam Arslan & Devecioğlu, 2010) was used in this study. Rubrics are often used in previous literature (Çalık & Ayas, 2005; Pell & Jarvis, 2001; Westbrook & Marek, 1992), and one developed by Abraham, Williamson, and Westbrook (1994) determined understanding levels by asking descriptive questions. The rubric used in this study is summarized in Table 1.

Table 1
Evaluation Rubric for Descriptive Responses

Level of Understanding (LU)	Score	Criteria
Sound Understanding (SU)	4	Responses containing all components of the scientifically accepted response
Partial Understanding (PU)	3	Responses containing some components of the scientifically accepted response
Partial Understanding with Alternative Conception (PU-AC)	2	Responses showing that the concept is understood but also containing alternative conceptions
Alternative Conception (AC)	1	Scientifically incorrect responses containing illogical or incorrect information
No Understanding (NU)	0	Blank, irrelevant, or unclear responses

To analyze students' answers to the question that required drawing, a rubric was developed based on Abraham, Williamson, and Westbrook's (1994) rubric for descriptive responses and an initial analysis of answers given to the third question was performed via the data collection tool and based on the study of Sağlam Arslan (2009) (Table 2).

Table 2
Evaluation Rubric for Visual Responses

Level of Understanding	Score	Criteria
Correct Depicting (CD)	4	Drawings reflecting all components of the scientific depiction
Partial Correct Depicting (PCD)	3	Drawings reflecting some components of the scientific depiction
Correct Drawings reflecting also Nonscientific Depicting (CD-ND)	2	Drawings reflecting scientific or partial scientific but also nonscientific depictions
Incorrect Depicting (ID)	1	Drawings reflecting wholly nonscientific depictions
No Depicting (ND)	0	Blank

Understanding levels were determined separately by the two researchers. Based on the reliability calculation formula of Miles and Huberman (1994), the percentage of case agreement between the two was calculated at 90% for description and 84% for visualization. Students' mental models concerning friction were determined with reference to defined understanding levels (see Table 3). To ascertain the model of understanding for any given student about solid friction, their levels of understanding related to "friction," "reasons for friction," and "interactions between molecules during the process of friction" were examined. Students' mental models were classified as scientific, synthetic, or initial (Vosniadou, 1994; Vosniadou & Brewer, 1992, 1994). In this process, understanding levels of 3 and 4 were described as sufficient, and understanding levels of 0, 1, and 2 were described as insufficient.

Table 3
Evaluation Rubric for Mental Models

Model of Understanding	Content	Level of Understanding
Scientific	Perceptions which coincide with scientific knowledge: answers at level 3 (PU or PCD) or 4 (SU or CD).	$\begin{bmatrix} 3 & 3 & 3 \\ 3 & 3 & 3 \end{bmatrix}$
Synthetic	Perceptions which partially coincide or do not coincide with scientific knowledge.	*All other posibilities*
Initial	Perceptions which do not coincide with scientific knowledge: answers at level 0 (NU or ND), 1 (AC or ID) or 2 (PU-AC or CD-ND).	$\begin{bmatrix} 0 & 0 & 0 \\ 1 & 1 & 1 \\ 2 & 2 & 2 \end{bmatrix}$

To understand the rubric given in Table 3, for example, the levels of understanding for Student A for each of the three cases were as follows: level 1 for friction; level 0 for reasons for friction; level 2 for interactions between molecules during the process of friction, and for Student B for each of the three cases were as follows: level 4 for friction; level 3 for reasons for friction; level 1 for interactions between molecules during the process of friction. Using the last column of the table, the model of understanding for Student A is the Initial Model and for Student B is the Synthetic Model.

Results

The findings were presented under two main headings: Students' understanding levels and students' mental models.

Students' Understanding Levels

Students' understanding levels concerning the questions are presented in separate tables. The students' understanding of friction is shown in Table 4, according to answers given to the first question of the data collection tool.

Table 4
Distribution of Friction Understanding Levels

Level of Understanding	Grade Level (f)				Total (f) (%)	
	9	10	11	12		
SU	-	-	-	6	6	2.79
PU	35	25	39	32	131	60.93
PU-AC	14	13	16	16	59	27.44
AC	6	-	-	2	8	3.72
NU	2	1	8	-	11	5.12
Total	57	39	63	56	215	100

An analysis of Table 4 shows that only a few of twelfth grade students were at the SU level. Students' understanding levels concerning solid friction were mainly categorized at the PU and PU-AC levels across almost all of the grades. Students classified at the PU understanding level (about 61%) generally explained solid friction as a force slowing an object in the reverse direction of movement, or as a force preventing movement. In other words, friction was regarded at the macro level. Almost no students considered microscopic level interactions. One student who scored a PU level stated, "*Friction is a force that affects a moving object or body reversely and decreases its velocity.*" Students classified at the PU-AC level (about 27%) identified solid friction as a force and offered alternative opinions. One student at this level indicated, "*It's a force affecting a force in reverse direction.*"

Table 5 shows students' understanding levels of reasons for friction, according to answers given to the second question of the data collection tool. Students at the SU level mentioned all factors from the curriculum, students at the PU level mentioned some factors, PU-AC students mentioned factors in the curriculum as well as non-scientific factors, and students at the AC level only mentioned non-scientific factors.

Table 5
Distribution of Understanding Levels Concerning the Reasons for Friction

Level of Understanding	Grade Level (f)				Total (f) (%)	
	9	10	11	12		
SU	19	11	29	21	80	37.21
PU	18	11	17	19	65	30.23
PU-AC	19	14	6	15	54	25.12
AC	1	1	4	1	7	3.26
NU	-	2	7	-	9	4.18
Total	57	39	63	56	215	100

As seen in Table 5, just over 37% of students were classified at the SU understanding level by identifying all reasons for friction completely; about 30% of students were classified at the PU understanding level by omitting some reasons. Almost one-fourth of students included factors that do not affect solid friction in their answers, such as the object's surface area or velocity. Also, when the changes in students' responses between grades handled, it is seen that students in all grades are generally classified in SU, PU or PU-AC understanding levels.

Students were asked to create drawings about the solid friction process to determine understanding concerning interactions among molecules between the object and surface. Table 6 shows the distribution of understanding levels, according to answers given to the third question of the data collection tool.

Table 6
Distribution of Understanding Levels Concerning Interactions between Molecules during the Process of Friction

Level of Understanding	Grade Level (f)				Total (f) (%)	
	9	10	11	12		
PCD	25	7	18	36	86	40.00
CD-ND	30	19	32	11	92	42.79
ID	2	12	6	9	29	13.48
ND	-	1	7	-	8	3.73
Total	57	39	63	56	215	100

As seen in Table 6, no student created a drawing showing a wholly scientific perception of the interactions occurring at the microscopic level between an object and a surface during friction. In other words, no students were classified at the CD level; however, 40% of students scored at the PCD level, with drawings showing some scientific information. These drawings were deemed to be insufficient because they showed (a) one-way interaction between molecules, emphasizing interactions either between surface molecules or between object molecules, or (b) no increase in the temperature of the object and surface due to molecule movement. Almost 43% of students included non-scientific aspects in their scientific drawings and were classified at the CD-ND level. Students at this level generally drew a decrease in the number of atoms of the object. Finally, just over 13% of students made non-scientific drawings and were classified at the ID level. Examples of students' drawings are shown in Figure 3.

Table 6 also shows that students in all grades are generally classified in PCD or CD-ND understanding levels. That is, the changes in students' responses in the whole grades have similar tendencies.

Students' Mental Models

Students' mental models, as determined in accordance with understanding levels defined for each subject area, are shown in Table 7.

Table 7
Distribution of Students' Mental Models

Model of Understanding	Grade Level (f) (%)								Total (f) (%)	
	9		10		11		12			
Scientific	6	10.53	3	7.69	10	15.87	18	32.14	37	17.21
Synthetic	31	54.39	21	53.85	41	65.08	28	50.00	121	56.28
Initial	20	35.08	15	38.46	12	19.05	10	17.86	57	26.51
Total	57	100	39	100	63	100	56	100	215	100

As seen in Table 7, more than half of the students had a synthetic mental model of solid friction. Almost a quarter of them had an initial mental model, and one-fifth had a scientific mental model. When mental models are compared across grade levels, there is a decrease in initial mental models and an increase in scientific mental models beginning in eleventh grade.

Discussion and Conclusion

An examination of students' mental models concerning solid friction was limited to the size and grade level of participants as well as to the three questions asked of them. Results of this study show that solid friction and students' perceptions may include alternative ideas and, therefore, the nature of certain mental models may be different from scientific attributes. Despite the fact that the majority of students did not have scientific mental models, synthetic mental models that included

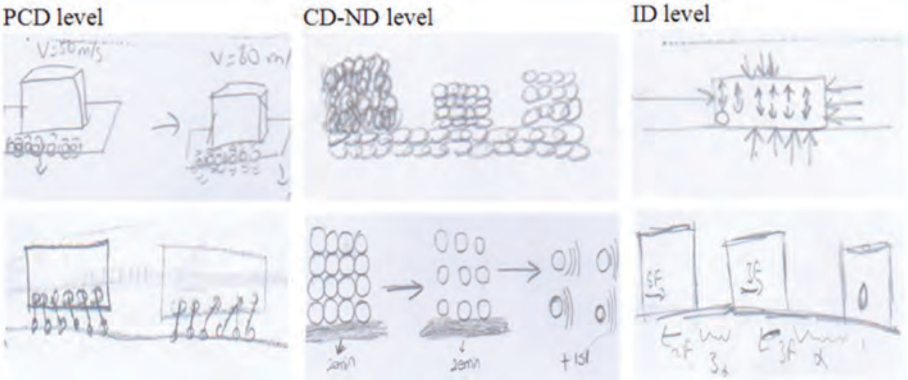


Figure 3: Samples of student drawings concerning interactions between molecules in the process of friction.

scientific perceptions demonstrate that they have acquired relevant scientific information. Students in lower grades had more initial mental models, with a decrease in this model appearing in eleventh grade.

While the ratio of synthetic and scientific mental models increases in eleventh grade, the ratio of scientific mental models increases in twelfth. Vosniadou and Brewer (1992; 1994) and Vosniadou (1994) emphasized that students with synthetic models have partially obtained scientific knowledge, which is supported through examinations of current physics teaching programs. Students in eleventh grade are introduced to internal energy related to heat and temperature, and they learn how molecules tremble when heated and, thus, how energy transfers superficially (Kurnaz et al., 2012, MoNE, 2011b). Therefore, students gain knowledge about what occurs between molecules during the solid friction process (the topic of the third question of the data collection tool), explaining the decrease in initial mental models. However, findings about understanding levels of students regarding interactions between molecules during friction clearly show that content presented at the microscopic level concerning internal energy is not enough to structure scientific perceptions about solid friction. In twelfth grade, students learn more details about energy transfer methods by examining movements of molecules (MoNE, 2011c, 2012), which explains the increase in scientific mental models. This finding, that content presented at the microscopic level improves students' understanding, is parallel to the findings of Kurnaz (2011).

In sum, the students participating in this study learned about the concept of solid friction at the macroscopic level during physics courses. In addition, they were indirectly informed about the issues of internal energy and energy transfer methods at the microscopic level. Findings may not be related to solid friction directly, but these findings indicate that students began to structure mental models about solid friction at the microscopic level beginning in eleventh grade. In this sense, instructors and facilitators should include interactions at the microscopic level when designing learning environments on the subject of solid friction. More specifically, teaching solid friction may be initiated with macroscopic presentations, interpreted at mesoscopic levels, and then deepened at microscopic levels. This case study could play a significant role in organizing and implementing forthcoming teaching activities for solid friction. In this process, using concrete real life examples and cognitive activities that uphold student thinking, discussions, and interpretations is recommended. The results of this study reflect the current status of solid friction presented at macroscopic levels, rather than the effectiveness of teaching solid friction directly at microscopic levels, which remains a topic to be examined in further studies. Thus, the results of this paper are not generalized but rather strive to be helpful to instructors. In this manner, it is recommended that teaching and learning conditions in existing learning environments across various high school grades should be undertaken, as well as improved alternative teaching materials to remedy student non-scientific mental models.

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