INTRODUCTORYCOLLEGE PHYSICS STUDENTS' MENTAL MODELS OF FRICTION AND RELATED PHENOMENA AT THE MICROSCOPIC LEVEL

We investigated introductory college physics students' mental models of friction and lubrication through semi-structured clinical interviews. Our results show that students' mental models of friction at the atomic level are dominated by their macroscopic experiences. Students often believe that friction is produced when two macroscopic surfaces come into contact and rub against each other. Friction at the atomic level then, according to these students, should therefore be just the mechanical interactions (interlocking or rubbing) of the atoms. These results will guide the design of teaching interview protocols that will enable students to develop metaconceptual awareness between the macroscopic and microscopic world and likewise enable us to study in more detail the dynamics of model construction/reconstruction of students in the context of friction.

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Introduction

At present, we are at the verge of several breakthroughs in nanoscience and technology. Challenging students to think of what is happening at the atomic scale is a great step in advancing the goals of nanoscience education. We report on students' mental models of friction and lubrication at the atomic level. Friction is a familiar concept to most introductory students and a part of their everyday experiences. Although friction on the microscopic scale has not yet been completely understood, nanotribologists are now establishing evidence of the disparity between friction at the microscopic and macroscopic level. We believe it is important that students learn that friction at the atomic scale is quite different from macroscopic friction. To accomplish this we need to establish students' existing mental models of friction at different length scales.

Specifically we tried to seek answers to the following research questions:

- What are the existing mental models of introductory college students regarding friction and related phenomena at the microscopic level?
- How do students build and use models in explaining common everyday phenomena related to friction?

The study of students' mental models has been and continues to be, a hot topic of research in cognitive psychology and science education. Mental models according to Johnson-Laird (1983) "are structural analogues of the world as perceived or conceptualized." Meanwhile, Gentner & Stevens (1983) argue that "mental models are related to human knowledge of the world and of how it works i.e., the way people understand some domain of knowledge." From Gilbert and Boulter's (1998) perspective, a model is a "representation of a target which might be an object, event, process or system." Vosniadou (1994) believes that "mental models refer to a special kind of mental representation, an analog representation, which individuals generate during cognitive functioning."

In our research we are defining mental models as students' way of understanding a certain physical phenomenon — friction. We believe that students construct these models in vivo while answering questions during an interview -- predicting and explaining why a system behaves in a particular way in a given context. This framework is consistent with that of Franco and Colinvaux (2000), Vosniadou (1994), Gentner and Stevens (1983) and Rouse and Morris (1986). Moreover, the term 'mental model,' in our research, actually refers to the model that we, the researchers have constructed to describe what we believe the students are thinking.

Embedded in the definitions of mental models above, is its private nature (Gilbert & Boulter, 1998; Franco & Colinvaux, 2000; Norman, 1983). This means that mental models seem to be inaccessible and that we can rely only on an expressed version of it which is often referred to as an expressed model. Expressed models represent selected aspects of phenomena and of our mental models. Figure 1 shows the interactive nature of the relationship between mental models, expressed models and phenomena (Buckley & Boulter, 2000)

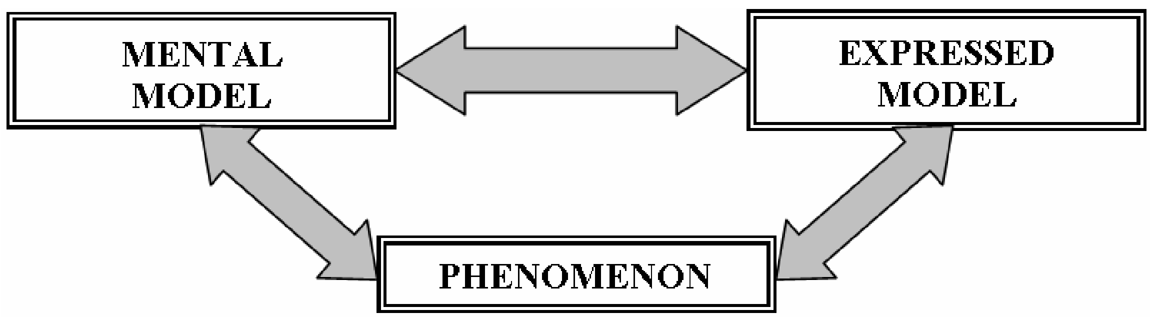


Figure 1: Interactive relationship between models and phenomena

In understanding the mental models of students regarding friction we conducted semi-structured clinical interviews and asked them factual and generative questions (Vosniadou, 1994) in various contexts. Several activities were presented to the students where they were asked to predict and explain what they think would happen. The different activities gave us different contexts in which we can probe deeper into students' understanding, and thus had a better access to their thinking. This also put us in a better position to assume that the students' expressed models that we have are a close representation of their mental models. In our final analysis, the categories of students' responses (mental models) from our interview were also looked into through the context of the features attributable to mental models as argued by Franco and Colinvaux (2000)

Aside from the mental models being private, Norman (1983) also stressed the distinction between individual's mental models and the analysis that researchers can carry out regarding these models. We couldn't disagree more with this issue on grasping mental models. In our research when we talk about mental models we actually refer to our own model of students' understanding that we discovered based on some expressed version of it. Like many other things that physicists try to describe, such as microscopic particles, we can never see or 'read' what is in a student's mind, but we can (as physicists often do) construct a model (based on experimental evidence) about what or how a student might be thinking based on what they tell us. Why do we researchers build models of student thinking? They do this for reasons similar to physicists. Such models (just like models in physics) can be useful, because they provide us with a vocabulary or framework to describe what a student may be thinking and what difficulty s/he has. Based on the models of what they think about a particular phenomena, instructors/curriculum makers can be in a better position to provide interventions that will help students reorganize pieces of their knowledge and eventually improve their existing mental model so as to have a deeper and more coherent understanding of a given phenomena.

Numerous studies (Abraham, Grzybowski, Renner, & Marek, 1992; Griffiths & Perston, 1992; Hesse & Anderson, 1992; Andersson, 1990; Unal, 1996) have been done to document students' ideas about particles and atoms. Relatively fewer studies (Eylon & Ganiel, 1990; Lee, Eichinger, Anderson, G.D, & Blakeslee, 1993) have been done to document students' use of models in explaining the behavior of bulk matter. Microscopic models of students in explaining real life phenomena needs further study. A study has yet to be done to document what students think about friction and lubrication at the atomic level. Our purpose in documenting students' models of friction and lubrication is to have baseline data or working hypotheses on how we can address the issues regarding the dynamics of model construction/reconstruction of students in a particular context. Also, results of this study can be particularly important in helping instructors design instruction in order to help students adopt a metaconceptual awareness of the quite different mechanisms of friction in the macroscopic and microscopic world.

Methodology

In order to elicit students' mental models, two one-hour semi-structured clinical interviews were conducted per student. The interview sessions were videotaped with permission from the students. A total of 11 students enrolled in a non-calculus based introductory physics classes were interviewed. Almost all students were life-science majors and already had instruction on atoms in previous science classes.

We pilot-tested our protocol with an expert and two other students and revised this protocol based on their feedback. We began our clinical interviews by asking students to slide their fingers across a wooden block and sketch the surface starting at the macroscopic scale and zooming in progressively to smaller length scales. Most of the students eventually realized that zooming in would get them to the atomic level. However, they were unsure at which length scale that would occur. Follow-up questions explored ideas about the:

- cause of friction at the atomic level,
- differences between kinetic friction and static friction,
- lubricating mechanism of oil,
- effect of surface roughness on friction, and
- effect of gravity on friction.

We used phenomenographic analysis (Marton, 1986; Svennson & J., 1983) as per which students' responses are grouped into naturally occurring categories based on their quotes and excerpts. The inter-rater reliability of the categorization was established by having two other experts do the categorization independently. A second layer of thematic analysis combined the categories of responses in different contexts in the interview to generate themes.

Results & Discussion

Cause of Friction at the Atomic Level

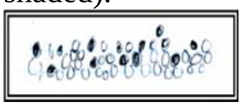
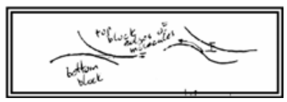
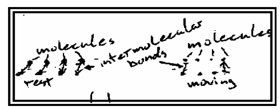
Students were asked to pull a wooden block over a plank. Interviewees talked about friction when explaining why they needed a finite force to start the block moving. Follow-up questions probed students' ideas about the causes of friction at the atomic level. Table 1 summarizes the models and provides a representative quote and sketch explaining the microscopic model. A majority of the students used the intertwining/interlocking and rubbing/sliding model to explain microscopic friction. An inter-rater reliability of 80% was established.

Why Static Friction is Greater than Kinetic Friction

In explaining why static friction is greater than kinetic friction, a majority of the students used skimming through the top model. Table 2 summarizes all of the models used by students to explain this observation.

Lubricating Mechanism of Oil

The two most dominant models (Table 3) that students used in explaining how oil reduces friction are the ball bearing and floating models. A majority of the students think that oil atoms reduce friction such as ball bearings or that they provide a floating barrier for the upper surface.

	MODELS		
	Intertwining / Interlocking	**Rubbing/Sliding**	**Breaking of Bonds**
Model Description	Friction is the force needed to pull an atom over the bumps due to intertwining or interlocking of atoms.	Friction is the rubbing or sliding of an atom past another atom.	Friction is the force needed to break the bonds between atoms of surfaces that come into contact.
Sample Sketch	The atoms of the wooden block (shaded) interlock with the atoms of the tabletop (not shaded). 	The atoms of the wooden block rub against the atoms of the tabletop. 	The atoms of the wooden block bond together with the atoms of the tabletop. 
Sample Quote	*"When you set it [the block] on top, it kind of settles in like goes into a neutral energy state. When I try to move it I got to pull them out so there will be some friction because there will be some particles getting intertwined (fingers of hand intertwining)."*	*"They (atoms) don't mesh together at all. They just sit on top of one another…they are touching but they don't interact any more than just the physical contact… one of them is moving and one of them isn't moving so they rub together."*	*"Well I would say friction is the bond between the atoms. I don't know if that's electronic or ionic bonding."*
# of Students	5 students	5 students*	3 students*

*Two students simultaneously used the rubbing/hitting and breaking of bonds model

Table 1: Models Explaining Static Friction

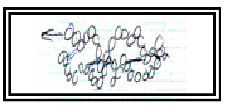
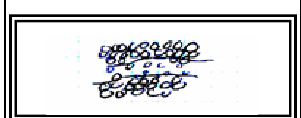
	MODELS			
	Skimming Over the Top	**Changing Downward Force**	**Getting Smoother**	**Fewer Bonds**
Model Description	Once the block has started moving, the atoms of the block just skim over the atoms of the other surface.	When an object starts to move the downward force decreases.	The surface would somehow get smoother once we started moving one of the surfaces relative to the other.	There are fewer bonds to break once the objects move relative to each other.
Sample Quote & Sketch	*"When you're moving it, they're gonna be not as intertwined."* 	*"When it is at rest there's more pressure between the atoms… when it starts moving, you have less force pulling down."*	*"The way this works basically is it is more rough when it wasn't moving than when it was."*	*"…they might not have enough time to form that (bond)… So there's less number of bonds to be broken."*
# of Students	5 students	1 student	1 student	2 students

Table 2: Models Explaining Kinetic Friction

	MODELS			
	Ball Bearing Model	**Weaker Bonds**	**Reduction of Bumps and Valleys**	**Floating Model**
Model Description	Oil reduces friction just like ball bearings.	With oil in between the surfaces, there is a weaker bond to break.	The atoms of the oil reduce the bumps and valleys thereby reducing resistance to movement.	Atoms of oil provide a floating barrier for the atoms of the wooden block.
Sample Quote & Sketch	*"I think it might be possible that they move past one another easier, but it could be that maybe oil molecules roll."*	*"… they don't exhibit as much intermolecular bonds between each oil molecule than between oil and wood molecules so they can move past one another easier than the wood on wood."*	*"Oil is not solid in a sense makes it a lot more flat to where nothing can stick out and go against stuff as it went by."*	*"Oil will help separate these bumps and valleys such that they don't have to interact with the full scale."* 
# of Students	5 students	1 student	2 students*	5 students*

*One student simultaneously used reduction of bumps and valleys and floating model

Table 3: Models Explaining the Lubricating Mechanism of Oil

To reveal students' thinking about friction and lubrication ,we began by probing their ideas of how surfaces look at different length scales. We had them slide their fingers across a wooden block and then asked them to sketch how the surface would look. Based on their initial sketch we then asked them to sketch how a portion of that surface would look if we kept zooming in. It was evident in the interview that students had not previously thought very much about this question, and they tend to come up with an explanation of the phenomena under investigation on the spot. Below is a sample transcript that demonstrates how one of our interviewees constructed and reconstructed models in explaining friction in different contexts.

> *I: What do you think is happening between the surfaces?*
>
> *BW: I would think that it seems like when it is just sitting there, the surfaces are somehow interacting and making one another almost more rough, I guess.*

Later, in the same interview…

> *I: You said earlier that if we have this wooden block rest on the wooden plank it would become smoother.*
>
> *BW: Yeah, I intuitively said it would become smoother. But the way this works basically it is more rough when it wasn't moving than when it was. I don't know on that one… I suppose that I don't know is not good enough.*

Then we probe deeper into BW's thinking by letting him explain what he thinks is happening between the two surfaces at the atomic level.

> *I: Could you possibly sketch what's happening between the two surfaces?*
>
> *BW: Yeah I could try. At the molecular level, you'd have like… edge of an atom would stick out like this* (see figure 2) *from one surface, from the bottom block and the surface of another atom kinda goes like… I don't know if that's enough to show it...*

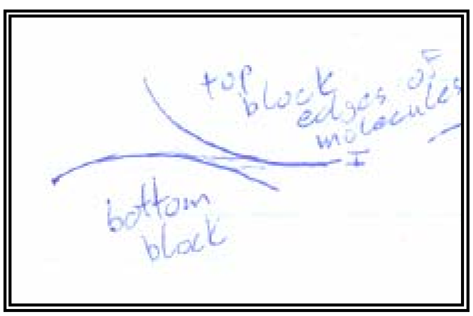


Figure 2: Sketch of the edges of atoms of the wooden block and the wooden plank

> *…They gonna hit one another right here where they cross each other's line* (draws sketch shown in figure 3)*… so like that and so there's gonna be a force needed to get it up over that bump. So, it's gonna go translate some of these to going up and some to going over or going across. So, that's gonna why the smoothness plays into it. Does that make sense? The more smooth it is, the less energy needed to get up this part because they're not smashed up so much like… say something like this and you have to go from here all the way to this. And so you've got a difference.*

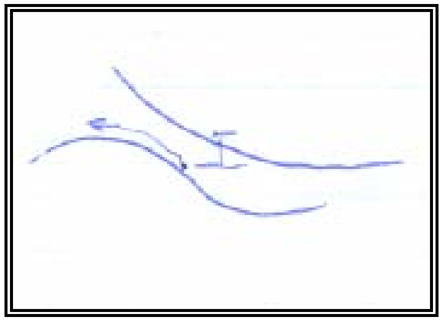


Figure 3: Sketch of the edges of atoms of the surfaces crossing each other's line

Based on the transcript above, we conclude that BW is using the 'getting-over-the bump' model to explain what causes static friction. We then asked him to explain his observation that the force needed to keep the block in motion was less than the force initially needed to start it moving from rest. Below is the transcript of our conversation.

I: You said that when we were just starting the block to move, we need to overcome these?

BW: Yeah. Overcome that but we should still have to overcome that every time you go over every atom or molecule. So that explanation is not quite good enough. I don't know…(pause). Unless perhaps when the two surfaces come into contact with one another, there's some sort of bonding going on. I don't know what sort of bonding between the two surfaces is happening but that would be another possible theory. So when it is just sitting there, there's kind of electrical bond or something built up, when they move faster they don't have time. I don't know.

In explaining kinetic friction BW constructed a model that was quite different from his previous model. He tried to make sense of the situation in terms of the previous model used but realized that it wouldn't work in this case. Thus, he was forced to come up with another model (breaking of bonds model) that could explain the situation at hand. It seemed like BW was aware that his initial model was inadequate and needs to be modified. It can be seen from the following transcript that BW tried to come up with a more coherent model to explain friction.

I: Could you please explain how the bonding would affect the force needed to start it moving and to keep it moving?

BW: ummm….. this one…So when it is just sitting, these two would form some sort of a bond which make them stick close together and kinda like what when you have like water all bunch together and you put a charge. Interacting with one another but they're not really making new molecules. I don't know what that effect was called. It's been too long. When they're sitting you kinda have a build up. You kinda have to overcome these little bonds enough to break them. When it

> *started moving let's say they might not have enough time to form that one and that one. So there's a less number of bonds to be broken.*

We then asked BW how the situation would be different if we put oil in between the surfaces.

> *BW: Maybe they don't exhibit as much intermolecular bonds between each oil molecule than between oil and wood molecules so they can move past one another easier than the wood on wood, wood and oil. I don't know. That might work.*

We can see from the above transcript that BW was trying to be consistent in his explanations. It seems to him that his previous model seemed to work in the two previous situations and he therefore tried to make it work in this new situation. Within the framework of conceptual change we see from the above interview data that students seem to cling to their model if it seems to be fruitful to them, i.e. it is able to explain their experiences. The interview transcript above also clearly provides evidence on the notion of the generative feature of mental models (Franco & Colinvaux, 2000). That is, the mental models previously constructed were evidently the basis in generating answers to subsequent questions in our interviews.

Emergent Theme: Macroscopic Ideas in Microscopic World

The theme 'Macroscopic Ideas in Microscopic World' emerged from the second level -- thematic analysis of the categories. We observed the persistence of students' responses that friction is simply due to physical contact of the atoms. When the five students with the interlocking model were asked what happens if the surfaces become atomically smooth they said that friction persists because atoms still physically rub against each other. Similarly, when students were asked to explain why oil reduces friction between two surfaces they often described the top surface as floating on the oil. This explanation is clearly based on their macroscopic experiences with flotation. Thus, students consistently transfer their knowledge from macroscopic experiences to explain microscopic friction.

Findings

Most of the students hold onto the idea that friction at the atomic level is simply due to mechanical interactions. This is evident from the models used by students in explaining static friction as to why static is greater than the kinetic and lubricating mechanism of oil. When students were asked to sketch what the smoothest surface would look like at the atomic level, they often drew atoms lining up. When asked if there was still friction when two such surfaces come into contact and move past one another, we often heard students say, "T*here will still be friction because there is still some contour in them (atoms.)*" Only one student cited electrical interactions as a possible source of friction.

Thus, for most students, what is true macroscopically must also be true microscopically. This general result is consistent with previous research (Andersson, 1990) on student understanding of the microscopic world. This result is also consistent with Franco and Colinvaux's notion that students' mental models are constrained by their worldviews. The mental models used by students to explain friction in the different contexts in the interview were evidently influenced by students' general beliefs systems that they held.

Our data also provides ample evidence to support the ubiquity of transfer. In constructing a model of surfaces at the atomic level we have seen students transferring what they have learned from their high school science and previous college physics courses. Students also transfer their everyday macroscopic experiences to the microscopic level. There were also instances where students engaged in near transfer, in that their explanation of a situation related to friction was dominated by their previous explanations in the interview. Students tended to transfer whatever explanation worked previously, as they strived to build on previously useful ideas. This result also provides support for the notion that mental models are generative.

Future Directions

Based on the results of this study we are currently designing and testing teaching experiments with the goal of helping students develop awareness of the many different aspects of friction in the macroscopic and microscopic worlds. The design of teaching experiments is anchored on the tenets of constructivist conceptual change -- first establish students' existing knowledge and then use it accordingly to promote conceptual change. The above results made us aware of the ideas of friction and lubrication that students bring into the classroom. In facilitating model reconstruction we will be guided by different cognitive conflict-based conceptual change instructional models (Cosgrove & Osborne, 1985; Champagne, Gunstone, & Klopfer, 1985; Chinn & Brewer, 1993). The teaching experiment can tell us what instructional strategies and tools can effectively contribute to the knowledge reconstruction of the students in the context of friction.

Although much research had been done to document students' preconceptions and how they can be changed (Hammer, 1994; Kesidou & Duit, 1993; Heller & Finley, 1992; Litowitz, 1991; Halloun & Hestenes, 1985; Goldberg & McDermott, 1986; McDermott, 1984) there are still several issues that need to be clarified regarding conceptual change. Particularly, there is little research that documents the dynamics of model construction/reconstruction by students in real time. The following issues regarding model building still need to be addressed:

- What external inputs (cues, hints, model-eliciting activities and other prompts) do we need to provide students to cause them to reorganize their knowledge?
- How do students use these external inputs in reorganizing their knowledge and reconstructing their mental model?
- What information from the students' memory (mental resources) gets activated by these external inputs?
- What prior knowledge or external inputs do students use in coming up with a model in explaining a specific phenomena?

We will address these and other questions within the context of microscopic friction in the next phase of our research.

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