

## **Writing as a Mediator for Conceptual Change: A Targeted Activity to Help Students Uncover Their Misconceptions in an Introductory Physics Class**

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### **Introduction: Theoretical Foundations for Writing as a Mediator for Critical Thinking in Science Classrooms**

The use of writing exercises in science classrooms to activate critical thinking and to achieve meaningful learning has been well documented in science education and cognitive science literature. Glynn and Muth (1994), in a comprehensive summary of the research on reading and writing to support science learning, claimed “the ability to understand and explain in clear language the meaning of fundamental scientific concepts is central to science literacy” (p. 1058) and further proposed reading and writing activities as “ideal media for engaging students’ minds and for fostering the construction of conceptual relations” (p. 1060). Meaningful learning is further described as the ability to carry out cognitive processes “that actively construct conceptual relations” between new and existing knowledge (p. 1060). The literature paralleling these perspectives on science learning is vast. The following, non-exhaustive sampling of that literature discusses the use of science writing to mediate critical thinking, an active construction of conceptual relations between new and existing knowledge, in order to achieve meaningful learning.

This negotiation between new and existing knowledge can be complex. Keys, Hand, Prain, and Collins (1999) claimed that “encouraging students to write is to encourage them to negotiate meaning and to construct knowledge” (p. 1066). In their research, which explores the use of Science Writing Heuristics (SWH), they concluded from linguistic evidence that students made “well-reasoned links between laboratory tests, observations and inferences, and were further able to capitalize on the power of writing to generate learning and science understandings” (p. 1066). One year later, Mason and Boscolo (2000), in a report on writing and conceptual change, explored whether fourth-grade students could “use writing as a means to express and compare ideas, and to reason and reflect on them in the process of scientific understanding” (p. 199). Using a control (no-writing) and an experimental group, which included a specific writing protocol as a teaching strategy for achieving a target concept of photosynthesis, they found that writing as a learning activity promoted deep conceptual understanding even at the primary school level. Qualitative and quantitative findings, from pre- and post-test questionnaires administered to both groups of students, showed among members of the experimental group a statistically significant increase in understanding of the target concept. The authors concluded that writing allowed the experimental group to “express and compare ideas, reason and reflect on them” and to “experience new concepts and make sense of their developing knowledge” (p. 221). On the other end of the academic spectrum, Stewart and Ballard (2010) examined learning gains by undergraduate physics students tasked with completing a written component of an exam. The performance of those students whose written solution to a problem contained more

words and fewer numbers positively correlated with stronger performances on the Conceptual Survey in Electricity and Magnetism. The performance of over 240 students showed that the amount of language used was “consistently and significantly positively related with test average and post-test score” on the survey (p. 9). The authors concluded that “the study provides support for continuation of efforts to get students to express their physics solution more completely and to use more linguistic descriptions in their solutions” (p. 8). This can be taken as further evidence that writing engages critical thinking, even quantitative critical thinking, more effectively than equations might. Other science education scholars found teaching that included established professional scientific practices to be a useful pedagogy. For example, Hoskinson and Caballero (2013), in their summary of three decades of Physics Education Research (PER), described how reading scientific literature, followed by writing and critiquing that literature, engages students in the “practice” of professional science, exposing them to more complex and “authentic” methods of problem solving. Addy, LePrevost, and Stevenson (2014), in a report that is also consistent with this notion, suggested that “another avenue through which to incorporate critical thinking” (p. 5) is to ask students to assess, in writing, claims made in science-related articles—in other words, incorporating both scientific reading and scientific writing in one exercise.

### **Science Writing to Achieve Conceptual Change**

In the previously cited work, conceptual change is taken, implicitly or explicitly, as evidence of learning. But what exactly is conceptual change? The answer is far from simple, as the research in this area continues to evolve. Conceptual change in the early model is described as the *enrichment* of an existing concept through the addition of new information to an existing conceptual framework (Vosniadou, 1994). When conceptual change does not occur, reconstruction or exchange of the existing knowledge base to a new conceptual framework is required for resolution of conceptual conflict (Hewson & Hewson, 1984). An addition to this model of conceptual change involves *revision* of an existing concept. Revision occurs when new information is inconsistent with an existing conceptual structure, requiring reconstruction of concepts for resolution. Failures in learning are more likely to happen when a revision of a conceptual structure is required (Vosniadou, 1994).

As this field of research has advanced, DiSessa (1998) has questioned the definition of “concept” and evolved a series of constructs, such as p-prims, nominal facts, narratives, mental models, and most recently coordination classes, to more precisely define it (DiSessa, 2005). More current conceptual change models do not focus exclusively on a concept as a single entity. Chi (2008), for example, described learner ontological categories, and further, how categorical shifts on the part of the learner are critical to achieving conceptual change. Vosniadou (2014) noted that learners hold a network or framework of understanding, a coherent knowledge system with limited predictive and explanatory power. Others, setting aside such theoretical mechanisms for describing conceptual change in pursuit of more operational identifiers, have instead suggested a conceptual change taxonomy based on qualitative, quantitative, and experimental criteria (Lappi, 2012). Still others have examined social underpinnings, pointing to interest and motivation as drivers for a change in framework (Sinatra, 2008). It is clear from these descriptions that differences in perspective and variations in key definitions make this area of research what Taber (2011) called “contested and messy” (p. 564), so much so that the publication of the *International*

*Handbook on Conceptual Change*, although more weighted towards the viewpoints of the editors, came as very necessary and highly applauded

Despite vastly divergent models of conceptual change, the idea that learners must, at some level, and to some degree, change their existing knowledge remains a reasonable idea. The notion that conceptual change leads to learning, and further, that higher barriers to learning result from conceptual conflict—the cognitive status resulting from having to exchange or reconstruct an existing incorrect or incomplete conceptual framework—has led researchers to investigate instructional strategies that explicitly make use of this conflict (Clement & Steinberg, 2002; Posner, Strike, Hewson, & Gertzog, 1982). In a later study, once again leveraging “conflict,” Kalman, Rohar, and Wells (2004) found value in the use of the argumentative essay to explain alternative or conflicting concepts. Different concepts to explain a particular phenomenon were developed by two groups in a cohort. After some debate and collaboration, the students were required to write a critique of the conflict as a homework exercise, an activity specifically introduced to have students critically think about, and consequently write about, conflicting possibilities. The researchers found a statistically significant improvement in this cohort as compared to a previous one in which no written critique was required.

All the findings cited above informed the redesign of a writing assignment routinely given to students in the large-enrollment physics classes at the University of California, Merced (UC Merced). The intention of the new assignment was to test the degree to which a linguistic analysis of student writing could be an indicator of a student’s knowledge framework and any resulting conceptual change.

### **The Case for a More Narrowly Focused, Conceptually Targeted Writing Assignment**

Since 2009, the introductory, large-enrollment physics classes at UC Merced have included a science writing requirement, largely motivated by the desire to uplift the potential research competencies and critical thinking skills of undergraduate physics students. The standard writing assignment requires students to select a subtopic in physics that they are interested in researching. The students research the topic, using peer-reviewed journals, and complete an essay, with appropriate citations. Selected topics must be consistent with the course; for example, students in a second-semester course that covers electricity and magnetism must select a subtopic for research that includes fundamental principles covered in a typical course in electromagnetics.

In the fall semester of 2016, an alternative assignment replaced the standard writing assignment in one of the large-enrollment introductory physics courses. The writing exercise was redesigned to be more narrowly focused, targeted to expose students to current PER literature that examined common student misconceptions about friction. For this new assignment, students are instructed to read research articles that report on *other students’* misconceptions of friction and then to compose an essay in response to specific prompts about their own concepts of friction as a result of the readings. This paper reports on the students’ written results of this targeted writing assignment.

### **Common Misconceptions in Understanding Friction**

Friction is a phenomenon that confronts us daily, and current models for understanding frictional effects are intuitive and easy to understand. But with technological advances that allow for investigating smaller and smaller phenomena, the model for friction needs to be

reconstructed to fit this smaller environment. Building a new conceptual framework around frictional models at the microscopic level is well needed and is the reason that this work on friction was selected for this study. Friction observed in everyday experience can be described “macroscopically.” Here, frictional phenomena are adequately demonstrated by sliding two surfaces past each other. A horizontal surface can glide by another horizontal surface at rest, under the influence of a sufficient pulling or pushing force. Once the force is removed, the object will come to rest due to the opposing nature of the frictional force. Clearly, some surfaces glide by each other easily, while some do not. In fact, an object whose surface is in contact with the surface of a plane that is inclined some angle relative to the horizontal may not move at all, until the angle of inclination is such that the effect of gravity exceeds the force of friction, which keeps the object stationary. A sneaker, for example, placed on an inclined plane that is made of wood, will likely not slip unless the angle of the inclined plane is appreciable. A piece of Teflon placed on the same angled plane will easily slip, and might even slip with very small angle deviations from the horizontal. These elements comprise the notion of static and kinetic friction and fall into the category of examples that demonstrate “macroscopic” friction.

Frictional dynamics at the macroscopic level, such as in the examples above, is sufficiently explained by magnifying two surfaces to a point that allows for observation of the “smoothness” of the surface. As we zoom in, the surfaces appear to be irregular, and these macroscopic frictional forces can be explained in terms of the “raggedness” of the individual surfaces that catch or snag each other as a force is applied to set the object in motion (Knight, 2004). If the raggedness at the interface of the surfaces is considerable, it is conceivable to imagine that a larger force needs to be applied to set the object in motion, and that such a force is much larger than one applied to surfaces in which the raggedness of the interface between the surfaces is not as pronounced. This macroscopic model is sufficient for many everyday scientific applications in manufacturing, construction, biomechanics, and a variety of other fields.

But this model does not tell the whole story in the age of nanotechnology, the science of the “very small.” Magnifying surfaces to dimensions that allow for inspection of this behavior at the interface between individual sheets of atoms indicates that frictional forces in this domain are not exclusively the result of atoms “snagging and catching” each other. In fact, the interatomic forces that are responsible for friction in this domain are largely electrostatic in nature: the result of interatomic bonding or redistribution of the arrangement of charges on microscopic structures. In this model, as “surfaces” glide by each other, interatomic bonds are alternately formed and then broken and then formed again. These actions serve to create the dissipative forces, known as Van Der Waals forces, that produce heat and impede or slow down motion.

The nature of frictional forces as modeled macroscopically versus microscopically is different. Interestingly, when students were asked to develop “mental models” for friction in these two distinctly different environments, many clung to the ideas that had formed for macroscopic environments, trying to adjust these ideas to the microscopic environment rather than adopting a new mental model sufficiently different from their macroscopic concept (Corpuz, 2006). This behavior supports the notion that students endeavoring to understand friction as a microscopic phenomenon modeled their microscopic environments largely with ideas formed from macroscopic thinking. Corpuz and Rebello (2011) found that some students using drawings and other guided visual activities were able to reformulate

their mental model or construct an entirely different model better suited to a microscopic environment. This movement to a new mental model is compelling evidence of reconstruction of the conceptual framework.

Because the Corpuz and Rebello (2011) study offers background elements in friction from both viewpoints—macroscopic and microscopic—as well as raw data generated by the students in the study—that is, their transcribed discourse and drawings—it was assigned as one of the readings in the targeted writing, both to inform students about the nature of friction and to expose them to misconceptions commonly held by *their peers*. The essay prompts were developed in support of unpacking notions about force and motion, potential conceptual conflicts, as demonstrated by the students in the study, and to probe knowledge frameworks held by students in order to identify any changes in concepts as evidenced by their writing.

### Study Design

Two PER publications were assigned for reading: “Talking to Learn Physics and Learning to Talk Physics” (Harlow & Otero, 2006) and “Investigating Students’ Mental Models and Knowledge Construction of Microscopic Friction; Implications for Curriculum Design and Development” (Corpuz & Rebello, 2011). The first article examined the ways in which students use the words *force* and *energy* and the degree to which these words are used correctly and consistently. The second article examined how students use mental models to develop descriptions of microscopic friction and the degree to which these descriptions are correct. Students read these articles and then write an essay addressing prompts that probe for evidence of a changed perspective on *friction*. The essay prompts contain the following four elements, in which students are asked 1) to report on the misconceptions demonstrated by students in the research study; 2) to summarize, correct, and complete physics concepts; 3) to find evidence of conceptual change in the students *about whom they read* in the research study; and 4) to independently explore other ideas about the research by using the citations in the reading. This approach is a meta-learning pedagogy designed to help students come to terms with their own misconceptions by reviewing the misconceptions of other students reported in the assigned readings. The essays were reviewed by two independent readers and classified by linguistic criteria. A rubric for scoring and coding the essays was constructed, based on linguistic evidence of the following two shifts in perspective: 1) the student’s knowledge framework was either reinforced or reconstructed and 2) any conceptual conflict was resolved.

### Methods

Students were asked to construct their essays in response to the following prompts:

1. What were the specific misconceptions and incomplete ideas held by the students in the articles that you read? You will need to specifically reference these and explain the evidence that the authors provide showing that misconceptions and incomplete ideas about friction are indeed held by the students in the study. For example, student dialogue and drawings are shown in each paper. Referencing these drawings and dialogue in your summary will help clarify these misconceptions.

2. What do you understand to be the correct and complete physics concept in each paper? Give a specific and precise example of how you understand the correct and complete concept and further give an example, again referencing the material presented in the paper, of how you now have a better understanding of the correct concepts.
3. In each paper, was there any evidence that the misconception of incomplete ideas was changed? If so, specify how this happened. Also specify the next steps that the authors suggest for continued research.
4. Each paper has a list of references. Choose one reference and show also how the material in the referenced paper supports the work of these two authors.

The students were given two weeks to complete their essays, which were submitted electronically. One hundred submitted essays were read three times each. The first pass eliminated those essays that were substantially incomplete or grammatically/syntactically unreviewable. The second pass established the basic scoring rubric. Two readers looked for patterns in the student responses to help develop coding categories. Each reader then established independent categories and assigned essays to those categories as appropriate. Both readers reviewed their categories, a final integrated list of categories and assignments to form the initial rubric was agreed upon, and a final review was completed using the integrated criteria. Discrepancies were handled individually until consensus of assignment was reached. Of the 75 essays reviewed by both readers, eleven essays required discussion for a final coding assignment. The following categories were teased out of the body of student work:

1. Explicit and clear statement causally relating Van der Waals forces and microscopic friction; quotes an outside reference to substantiate this understanding.
2. Explicit and clear statement causally relating Van der Waals forces and microscopic friction.
3. Explicit and clear statement causally relating electrostatic forces and microscopic friction.
4. Statement relating Van der Waals forces to friction, not necessarily causally, and accompanied by other contradictory elements.
5. Clearly articulates that the misconception about microscopic friction is still held.

Essays populating categories 1, 2 and 3 provide evidence of correct knowledge and that students, as a result of this reading and writing assignment, may in fact have learned the words "Friction is caused by Van Der Waals forces," and further, that they understand the causal relationship between Van der Waals forces and microscopic friction. But caution should be taken before accepting these statements as evidence that a complete restructuring of concepts occurred. Instead, these statements are declarative sentences in support of correct answer-making, which may or may not necessarily correlate with correct sense-making or a shift in understanding. Therefore, a secondary rubric was created to look for an explicit understanding of the underlying causes of microscopic friction and the difference between this model of friction and the macroscopic model, as this is taken as evidence of the

existence of a more complex conceptual framework perhaps restructured through the process of writing. The following categories for the secondary rubric are given below:

1. Linguistically compares and contrasts microscopic models of friction with macroscopic models.
2. Linguistically claims, or owns, the knowledge that differentiates microscopic from macroscopic friction.
3. Acknowledges and explains the conceptual conflict that students in the study held for microscopic friction.

### Data and Summarized Results

Table 1 shows the number of essays that populated each category of the initial rubric. A clear majority of the student essays (60%) demonstrated sufficient linguistic evidence to place them in categories 1, 2 or 3.

Table 1 *Initial Rubric*

Category	Description	Coding criteria	Essays/75
1	Explicit and clear statement causally relating Van der Waals forces and microscopic friction; quotes an outside reference to substantiate this understanding	Keywords and phrases sought: "friction is a result of/from/because of/ due to/caused by/since/ Van der Waals forces"	8/75
2	Explicit and clear statement causally relating Van der Waals forces and microscopic friction	Same as category 1 with no outside reference	26/75
3	Explicit and clear statement causally relating electrostatic forces and microscopic friction	Same as category 1 without explicit statement of Van der Waals forces	14/75
4	Relates Van der Waals forces to friction, not necessarily causally. Accompanied by other contradictory elements	Conflicting, incorrect physics concepts regarding microscopic friction	15/75
5	Clearly articulates that the misconception about microscopic friction is still held	Active voice statement that microscopic friction is governed by macroscopic models	12/75

As seen in Table 2, many students directly acknowledged the conceptual conflict of the students in the study, but fewer students personally claimed ownership of knowledge or of a previously held incorrect concept and subsequent replacement with correct notions. Notable, however, in all of these cases, was the linguistic ability with which some students made clear the contrasts between the set of conditions governing the macroscopic model and those governing the microscopic model. Beyond the initial rubric, by which student statements were sorted according to the causal relation between Van Der Waals forces and microscopic friction, this secondary rubric sorted responses based on a *comparing and contrasting* of the concepts governing both macroscopic and microscopic models of friction. This ability to linguistically differentiate between the two models is taken as evidence of the existence, and perhaps the preliminary structuring of, a more complete conceptual

framework. Only three categories were designated, and these are shown in Table 2. It is important to note that of the 75 reviewed essays, 45 demonstrated category 1, 2 or 3 linguistic markers from the initial rubric, and these essays were the only ones passed through the secondary rubric for ranking, as these essays contained correct notions about the two frictional models.

Table 2 *Secondary Rubric*

Category	Description	Coding criteria	Essays/45
1	Linguistically compares/contrasts microscopic and macroscopic models of friction	Sentence structure shows comparison/contrast efforts to differentiate the frictional models	12/45
2	Linguistically claims, or owns, the knowledge that differentiates microscopic from macroscopic friction	I know/ we know/ I believe/ I understand/ keywords are explicit, demonstrating personal ownership of the correct concept or an evolved concept	8/45
3	Acknowledges that students in the study held conceptual conflicts for microscopic friction and describes such conflict	References misconceptions of students in the study	15/45

## Discussion

In the absence of any ability to make direct observations of student thinking, writing assessment is a reasonable tool of measurement, although as Hogan (1996) noted quite correctly, “Our understanding of student thinking is constrained by our reliance on language as the primary source of data. By analyzing students’ verbalizations, we change raw data into a synthesis that is our thinking combined with evidence of their thinking” (p. 947). Nevertheless, the rationale for evaluating learning through language analysis is fairly well grounded in science education research, and, as suggested by Halliday (1994), a pioneer in functional linguistics, is rooted in the notion that “language is the essential condition of knowing, the process by which experience becomes knowledge” (p. 94). These are the ideas that informed the assessment of the targeted writing assignment: to make use of linguistic evaluations of the writing as “data” for student thinking, and from that assessment, determine if the writing activity helped a student negotiate the cognitive complexities of restructuring an existing and incomplete concept.

The rules governing the structure of language can provide clues to better understand the complex cognitive mechanisms at play as a student reinforces a knowledge framework or restructures or incorporates new concepts into his or her knowledge framework. If a student constructs a simple declarative sentence, a statement of fact, such as “microscopic frictional forces are electrostatic in nature,” we can, from a linguistic analysis, conclude only that the student has restated this correct fact. But this does not tell the whole story as it is not evidence that there are *not* more complex underlying connections made by the student; it’s just that we cannot see direct evidence of those connections or assume that they are being



made, or not. These are the limitations of evaluating “student thinking,” even indirectly, by examining written language. However, when a student writes a sentence with a complex structure, requiring the use of subordinating conjunctions to complete logical connections between clauses, a linguistic analysis provides evidence of causal thinking. For example, a sentence such as “The macroscopic model of friction is due to mechanical forces, while the microscopic model is caused by Van Der Waals forces” provides more information about student thinking, as there is more “data” gleaned from the way in which this sentence is structured. The implied causal relationship between friction and forces, and the comparative description of both frictional cases, demonstrated by both lexicon and syntax that the student has resourced to describe in writing their knowledge framework, is largely due to the rules governing the structure of language.

Explicit examples of these writings and their category assignments are shown in Table 3 and Table 4. Table 3 shows category assignments as described by the initial rubric while Table 4 shows category assignments as described by the secondary rubric. Each statement contains keywords or sentence structure criteria assigned for each category. In all cases, specific keywords, such as subordinating or coordinating conjunctions, or comparison/contrast sentence structures were sought-after linguistic markers to assist in assigning the statement to a particular category.

Table 3 *Sample Student Writings Categorized by Initial Rubric*

Category	Student sample
1	<p>Student A: “To expand, friction consists of an electrical force between the molecules in varying surfaces (Wolfson). Studies indicate that friction at the microscopic scale is <u>due to</u> electrostatic forces and specifically involves mediation by van der Waals interactions.”</p> <p><i>Notes: Correctly identifies friction as resulting from, or mediated by, Van der Waals forces and quotes an outside source. Notes the causal relationship between Van der Waals forces and microscopic friction. Keywords: “due to”</i></p>
2	<p>Student B: “Of course, we know that microscopic friction is <u>not due to</u> such things, but instead of the van der Waals reactions between the atoms of the respective surfaces. The correct reality of what’s going is that while there is a reality that is occurring on the visible, observable, we know that electrostatic van der Waals bonding between the atoms is <u>what actually causes</u> friction microscopically.”</p> <p>Student C: “[students] would view friction at the micro- and macro- scale in the same way when in fact they are very different; <u>whereas on</u> the macroscale friction it uses contact forces, and Van der Waals interactions at the microscale. The second article on friction enlightened my knowledge on the explanation of microscale friction”</p> <p><i>Notes: Correctly identifies friction as resulting from Van der Waals forces. Notes the causal relationship between Van der Waals forces and microscopic friction. No outside source used. Keywords: “not due to,” “whereas,” “what actually causes”</i></p>
4	<p>Student E: “The friction on an atomic level is actually <u>caused by</u> Van der Waal interactions. This theory states that molecules repel each other at close range. So there exists <u>an atomic repulsion</u> between the two surfaces when they are rubbing against each other. Students made the mistake of evaluating atoms as they would macro-sized objects. However, interactions are different on the atomic level.”</p> <p><i>Notes: Relates Van der Waals forces to friction but followed by many contradictory/incorrect physics concepts. Key words “caused by,” “atomic repulsion”</i></p>

5	<p>Student F: “I agree that surfaces at the microscopic level would be seen as atoms that were put together with many irregularities. The irregularities convinced me to believe that friction is due to the peaks and troughs of surfaces’ shapes that intertwine or interlock with one another for a brief moment in time. I agree with the intertwining-interlocking of atoms model and believe that is the correct physics concept of friction.”</p> <p><i>Notes: Maintains the original misconception—that friction at the microscopic level is described adequately by mechanical interactions such as the intertwining and interlocking between atoms.</i></p>
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Table 4 Sample Student Writings Categorized by Secondary Rubric

Category	Student sample
1	<p>Student G: “Friction, at the macroscopic scale, is largely driven by the mechanical interactions between two surfaces, but at the microscopic scale friction is caused by electrostatic van der Waals interactions.”</p> <p><i>Notes: clear comparison/contrast between two models. Keyword: “but.” Coordinating conjunction “but” links equally weighted clauses, characteristic of comparison/contrast.</i></p>
2	<p>Student B: “Of course, <u>we know</u> that microscopic friction is not due to such things, but instead of the van der Waals reactions between the atoms of the respective surfaces. The correct reality of what’s going is that while there is a reality that is occurring on the visible, observable, <u>we know</u> now that electrostatic van der Waals bonding between the atoms is what actually causes friction microscopically.”</p> <p>Student C: “they [students in the study] would view friction at the micro- and macroscale in the same way when in fact they are very different; whereas on the macroscale friction it uses contact forces, and Van der Waals interactions at the microscale. The second article on friction <u>enlightened my knowledge</u> on the explanation of microscale friction”</p> <p>Student I: “they [students in the study] are explaining how friction can be explained very differently when looking at it at a microscopic level such as at the atomic level than it can at a macroscopic level or what we can see with our own eyes. <u>I believe</u> that friction can be explained through the bonding model. <u>I believe</u> that as bonds break or become weaker to break, less friction will occur.”</p> <p><i>Notes: Clear comparison/contrast between two models. Owns the knowledge. Key words: “we know,” “I believe,” “enlightened my knowledge”</i></p>
3	<p>Student J: “Once again, the students have a common misconception here because they don’t think that at the microscopic level whenever bonds from atoms are broken that is what causes the friction.”</p> <p><i>Notes: reports accurately on the student misconceptions in the study.</i></p>

As shown by Table 3 and Table 4, the study offers the opportunity to reflect on the linguistic evaluation for a deeper understanding of how students use written language to “make sense” and construct knowledge. Consider the following summarized evaluation of the essays: 1) Of the written essays, 55% (45/75 essays) demonstrated written evidence of causal relationships between Van der Waals forces and frictional effects (Table 1), and 2) 26% (12/45) of these showed additional linguistic evidence of clear and correct differentiations between the two physical models. Note specifically students B and C; these are examples of essays that were classified as either category 1, 2 or 3 of the initial rubric, followed by a category 2 assignment from the secondary rubric. Further inspection of Table 2 shows that while fewer students (8/45) personally acknowledged holding any initial

conceptual conflict between microscopic and macroscopic frictional models or a concept that was ultimately restructured, more than half of the 45 essays demonstrated either an accurate description of the two models (12/45) or an accurate description of the conceptual conflicts held by students about whom they were reading in the study (15/45).

### Conclusion

Writing in the physical sciences at the college level may not be a routine part of pedagogy, but when it is used, as shown by the various studies cited in this work, the results are encouraging and clearly in support of improved learning gains. The looming question, and the limitation of this particular research, is whether or not learning, defined as conceptual change, occurred. The results show that only 8 of the 75 essays demonstrated evidence that a complete change in a concept occurred. But these results do not provide evidence that this change did *not* occur in the other 67 essays—we just cannot observe it directly, the clear limitation of this study in particular, and of measuring student thinking in general. Nevertheless, the results do support the existence of knowledge frameworks of varying degrees of complexity in a majority of students, as evidenced by the writing. The linguistic resources identified in the writing do provide clues about the structure of the student's knowledge framework, especially to the degree that these frameworks contained correct causal relationships and accurate descriptors of the two distinctly different models; and this was demonstrated in more than half of the reviewed essays.

Further research is needed here, as this type of research is qualitative in design and outcome. A redesign of this study, using a control group (reading but no writing) and an experimental group (reading and writing) is a reasonable next step. A linguistic analysis of the experimental group, accompanied by pre-test and post-test for both groups, designed to measure students' prior knowledge of microscopic friction, could provide statistical evidence for the efficacy of this particular reading-writing exercise to mediate learning through conceptual change of any prior knowledge. Revised essay prompts, designed to more deeply probe the existence of conceptual conflict, accompanied by student interviews, both pre- and post-essay, could provide additional qualitative and quantitative data regarding the mediating role that writing plays in developing the critical thinking skills needed to negotiate conceptual reframing.

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