Changing the notation that represents a force changes how students say it

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To facilitate both learning about forces and coordinating forces with the system schema, force symbols in University Modeling Instruction carefully represent forces as detailed descriptions of interactions. For example, $\vec{F}^{g}_{E\to B}$ represents the gravitational force by Earth on a ball, where "g" represents gravitational (i.e. the type of interaction), "E" represents Earth, $\rightarrow$ represents "by" and "on", and "B" represents ball. Although students are taught to say $\vec{F}^{g}_{E\to B}$ as "gravitational force", audio data from student-led whole-class discussions shows that more than 40% percent of the time $\vec{F}^{g}_{E\to B}$ was referred to as "force gravity" instead. Symbols for contact force, such as $\vec{F}^{c}_{H\to B}$, were also similarly referred to as "force contact" rather than "contact force" more than 40% of the time. Because language plays such a crucial role in learning physics, several years ago, as an experiment, the notation was changed from $\vec{F}^{g}_{E\to B}$ to ${}^{g}\vec{F}_{E\to B}$ to make it more closely match how it is to be read. After this experimental notation switch, student use of "force gravity" dropped to less than 2%, while use of "force contact" completely disappeared. While we make no claims that helping students read symbols more effectively also facilitates their learning about forces, it is clear that the simple change in notation was extremely effective at solving the reading problem.

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I. INTRODUCTION

A core principle of University Modeling Instruction (UMI) is the introduction, use, and coordination of multiple representations [1-5]. Quality representations that are consistent with each other are vital for helping students build quality scientific models, a central goal of UMI [6]. In addition, students who are comfortable using a range of representations in problem solving better approximate physics experts, who routinely create many different representations (e.g. mathematical, graphical, diagrammatic) in the analysis of a single problem [7,8].

We will focus on just one representation in this paper: the symbol for force. Because learning about force is extremely difficult [9-11], and to help students coordinate forces with the system schema, force symbols in UMI carefully represent forces as detailed descriptions of interactions [2, 3]. In listening to how students referred to forces in classroom discussions, however, we noticed that they frequently did not read the symbol as it was intended.

Because proper use of language plays such a crucial role in learning physics [12], we wondered if we could help students improve their reading of force symbols. Thus our research question was: does the way notation for a force is written effect how students say the force? To answer this question, we changed the notation in a University Modeling Instruction (UMI) classroom, and looked to see if student speech patterns changed. We found a very clear effect.

In the rest of this paper we briefly explain how UMI teaches force as a description of an interaction, describe the classroom context for this study, present our initial results comparing data from two different years of the same course from before and after the change in notation, and end with a discussion of those results. Note that we do *not* address the further question of whether or not helping students read symbols better also facilitates their learning about forces.

II. FORCE AS A DESCRIPTION OF AN INTERACTION

A. A Coordinated Approach

University Modeling Instruction defines force as: one way to describe the interaction between two objects. To help visually represent that complex idea, UMI developed the System Schema, which shows all objects and interacions of interest for a given physical situation [2,3]. It is a first level of abstraction after a pictorial representation, and serves as a conceptual bridge from that concrete representation to more abstract representations like force diagrams and Newton's Laws. When working a problem, students are encouraged to start with the schema and build their force diagrams from it.

Figure 1, taken from reference [3], shows a typical problem from a university introductory physics course represented three different ways. As described below, all three representations are strongly coordinated with each other, especially the force symbols with the system schema. This is to help students build a consistent and coherent model while providing them with multiple ways to check their answer. Consistency is a narrative that runs through all representations of a given model in the UMI classroom.

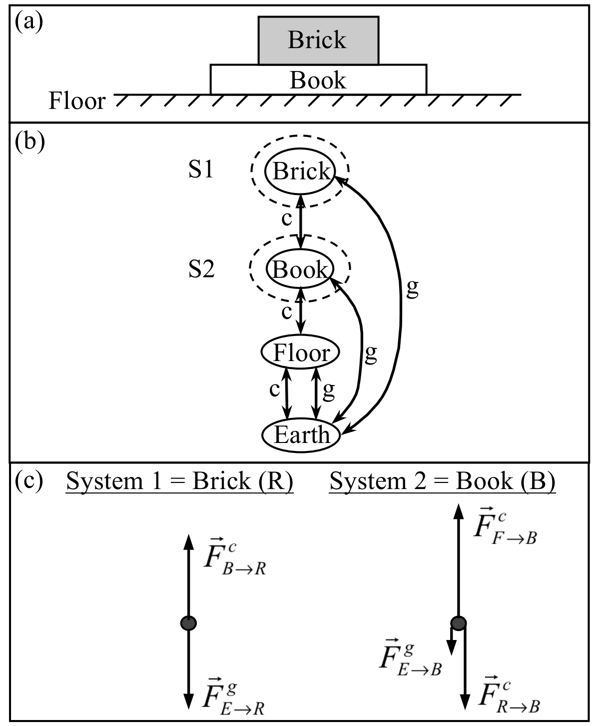

FIG. 1. (a) Pictorial representation of a physical situation. All objects are at rest. (b) System schema of this physical situation, with two of many possible systems [13] identified. The dashed ellipses represent system 1 (S1) and system 2 (S2) respectively. "c" labels a contact interaction, and "g" labels a gravitational interaction. (c) Force diagrams for the two systems identified in (b). In a force label "c" means contact, "g" means gravitational. Also, for this particular scenario "B" means book, "R" means brick, "E" means earth, and "F" means floor. For example, the symbol $\vec{F}^{c}_{B\to R}$ is read as the contact force by the book on the brick. The mass of the brick has arbitrarily been chosen to be three times the mass of the book, so $\vec{F}^{g}_{E\to R}$ is three times the length of $\vec{F}^{g}_{E\to B}$.

The two crucial ways a system schema and a force diagram coordinate follow directly from the UMI definition of force. The first is that for each interaction that crosses a system's boundary (the dashed ellipses in Figure 1b) there is one force exerted on that system. For example, three interactions cross the Book's system boundary, so the Book's force diagram should have three forces in it. If those numbers do not match, the student has direct feedback that they made an error somewhere.

The second way is that each force symbol in a force diagram describes only one particular two-headed interaction arrow in the schema and the two objects it connects. The symbol does this by identifying (i) the type of interaction it is describing (contact or gravitational here), (ii) the two objects at either end of the interaction arrow, (iii) which object is exerting a force on the system, and (iv) the system itself.

As a result, the super-script and sub-script in each force symbol make excellent bookkeeping devices when constructing a force diagram from the system schema. The super-script should match the type of interaction ("c" or "g") the force is describing. The second letter in the subscript (R for the Brick, and B for the Book) should represent the system of interest. It then follows that this second letter should be the same for all the forces in the force diagram for that system. For example, in Fig. 1c, the second letter is B for all forces acting on the Book. If the second letter differs within a given force diagram, then the student has made an error and gets direct feedback to that effect from seeing the inconsistency in their symbols. Finally, the first letter in the subscript should match the object outside the system at the other end of the interaction arrow the force is describing.

Because language plays a crucial role in learning physics, students are also instructed on how to "read" a force symbol. For example, $\vec{F}^{g}_{E\to B}$ from Figure 1c is read as "the gravitational force by Earth on the Book". This locution emphasizes the idea of force as a *description* of an interaction between two objects: the type of interaction (gravitational) is explicitly read, and the two objects involved in the interaction are also explicitly mentioned (Earth and Book) in a cause and effect manner (*by* Earth *on* the Book). This reading emphasizes that force is not a disembodied thing and that objects do not possess force or give force (in contradistinction to an impetus model of force that many novices bring into a college physics course [9, 14]), but rather that objects merely exert forces on other objects.

B. The Problem and the Intervention

As we attended to student discourse in the classroom, however, we noticed that some students occasionally referred to a $\vec{F}^{c}_{B\to R}$ as "force contact", or a $\vec{F}^{g}_{E\to B}$ as "force gravity" (they never said "force gravitational"). That is, they read the symbols literally, from left to right, which is an extremely reasonable thing for them to do. Not to get into grammar too deeply, but those phrases are deceptively close to "force of contact" or "force of gravity" and such language could potentially reinforce student's novice preconceptions and interfere with their ability to construct a more expert-like understanding of the force concept.

For example, could such language possibly lead students to think that "contact" and "gravity" exert forces rather than actual objects? Or could it possibly lead them to think that "contact" and "gravity" "possess" force and give it or transfer it to various objects, thus reinforcing the problematic impetus model of force? Further, "gravitational" should be preferred over "gravity" because it is an adjective and is thus descriptive, whereas "gravity" is a noun whose use could lead to the possible problems as described previously. These are rather subtle, but potentially important points. And if there is a bi-directional interaction between language and thought [15-17], then it is important that we attend to the problem. Perhaps some students would somehow benefit if we could remove a possible impediment (incorrect reading of a symbol) to the challenging task of learning the force concept.

We wondered if changing the symbol for force would change the way students said it. If they were literally reading the symbol from left to right, why not put the super-script interaction label on the left, so that it would be the first thing they might process when reading the symbol in a conventional English fashion? Thus, the next year we taught the course we did just that. The force label was introduced as ${}^{c}\vec{F}_{B\to R}$ or ${}^{g}\vec{F}_{E\to R}$ instead and used like that the entire year. Then we compared data to see the effect of the intervention.

III. METHOD

A. Classroom Context

The context for this study is the calculus-based introductory physics course taught using UMI and taken by all science majors at Drury University. The heart of UMI is Modeling Discourse Management (MDM) [18], a learning-community approach that explicitly focuses on the epistemology of science. It is designed to help students understand that the conclusions of science are tentative and evolving and that knowledge and understanding of meaning are constructed and shared through dialogue with others. In MDM, students work in small groups to create a solution to the same problem on a 2'x 3' whiteboard. They then sit in a large circle with their whiteboards held facing in and conduct a student-led whole-class discussion ("board" meeting) to reach consensus [19, 20]. Each

B. Data

For our initial data, we looked at the year before the change in notation and the year after. We identified seventeen problems that were used in class both years. We (DS) listened to audio recordings of these thirty-four board meetings and tabulated counts on the different ways students referred to the symbols for contact and gravitational forces. We also attempted to count how many different students actually said a particular utterance (*N* in Tables I & II). We were able to determine *N* for 2015-2016, but have not yet determined it for 2016-17. In 2015-16 there were 703 minutes of audio in total for all seventeen problems and the average problem lasted 41 minutes, while in 2016-17 there were 606 minutes in total and the average problem lasted 35 minutes.

We only had audio of board meetings, we did not have video. But despite an occasional difficulty in hearing differ-

TABLE I. The number of times during a given problem that a particular utterance was said when referring to a contact force. Quotes indicate verbatim what was actually said. A blank means that that particular utterance was not said during that problem. Note that "force contact" is said 79 times in total when the old notation is being used but is not said at all when the new notation is being used. Class size in 2015-16 was twenty-seven and in 2016-17 was twenty-eight.

	2015-2016 (Old Notation)						2016-2017 (New Notation)		
Problem Name	"force contact"	N*	"contact force"	N	"contact"	N	"force contact"	"contact force"	"contact"
collision lab			6	2	1	1		9	1
man-scale			5	4	3	2		30	4
ball thrown up			7	5				2	
N2 lab	6	3	1	1				6	2
give force?	4	3	16	12	3	2			
Pam-Chris	3	1	2	2	4	2		11	2
elevator			3	1	2	2		4	3
quick little problem			3	3	7	5		20	1
hand-book-wall	6	5	8	4	1	1		22	1
quant car-hill-rest	4	3	1	1	2	2			
anja-barb-cole			2	2				1	
child climbs rope	7	3	1	1				7	
scale weight	8	3	8	4	1	1		13	
atwoods	21	9			1	1		45	
quant ball thrown	3	3	1	1				11	
low f cart on ramp	9	4	2	2				3	1
quant cart-ramp	8	4							
Totals =	79		66		27		0	184	15

* N = estimated different number of students who said this. Not yet determined for audio from 2016-17.

TABLE II. The number of times during a given problem that a particular utterance was said when referring to a gravitational force. Quotes indicate verbatim what was actually said. A blank means that that particular utterance was not said during that problem. Note that "force gravity" is said 45 times in total when the old notation is being used but is said only once when the new notation is being used. Class size in 2015-16 was twenty-seven and in 2016-17 was twenty-eight.

	2015-2016 (Old Notation)						2016-2017 (New Notation)		
Problem Name	"force gravity"	N*	"gravitational force"	N	"gravitational"	N	"force gravity"	"gravitational force"	"gravitational"
collision lab			3	2	1	1		4	
man-scale			7	5				17	4
ball thrown up			11	6	1	1		3	
N2 lab								2	
give force?	2	1	4	3	7	4		2	1
Pam-Chris	2	1	3	2	1	1			3
elevator	2	1			4	3		4	5
quick little problem	1	1	2	2	4	4		5	3
hand-book-wall			3	3				8	13
quant car-hill-rest	6	2	2	2					
anja-barb-cole	2	1	1	1					
child climbs rope	6	3	1	1	1	1		3	2
scale weight	5	3	2	1	2	2	1	8	
atwoods	4	3			2	2		12	3
quant ball thrown	2	2			2	1		8	1
low f cart on ramp	5	2			1	1		1	1
quant cart-ramp	8	5	1	1				1	1
Totals =	45		40		26		1	78	37

* N = estimated different number of students who said this. Not yet determined for audio from 2016-17.

ent students in the different recordings, we are confident in both kinds of counts (number of utterances as well as *N*). To get an estimate on the uncertainties for both we plan to have a different researcher listen to the audio and compare their counts with this set of data, but we have not yet done this. However, given the stark difference in counts for "force contact" and "force gravity" from before the notation change to after, we do not think any uncertainties in those counts will be very relevant to any conclusions we might make in this paper.

IV. DISCUSSION

Tables I and II show the striking results. Before the notation change "force contact" utterances accounted for about 46% of the references to contact forces (if we include "contact" in the same category as "contact force") or 55% (if we ignore the "contact" counts), while "force gravity" utterances accounted for about 41% of the references to gravitational forces (if we include "gravitational" in the same category as "gravitational force") or 53% (if we ignore the "gravitational" counts).

There is some ambiguity in the "contact" and "gravitational" categories. Based on context clues, when students say either of those words, they are at least sometimes actually referring to interactions (in the schema) rather than to forces themselves. But because we only have audio, we are not always able to distinguish between the two uses.

There are many different things to notice in the data shown in Tables I and II. For example, there are a handful of different students who use "force contact" and "force gravity". That is, *N* varies from 1 up to 9 for "force contact" and from 1 up to 5 for "force gravity". Early on only one student is saying "force gravity", but more start using that locution in later problems.

It is very interesting that during the first three problems of the semester related to force (collision lab, man-scale, ball thrown up) there are no mentions of "force contact" or "force gravity" at all. It is only after the class does a lab related to Newton's Second Law (N2 lab) that students start to use those problematic locutions. It's possible this is because in addition to asking students to make well-labeled force diagrams, the first three problems also explicitly ask students to write out how they should read the symbols. There is an explicit requirement about reading the symbols that gets dropped for later problems. We could test this hypothesis by explicitly requiring students to write out how they should read the symbols throughout the sequence of problems related to force.

It is also possible that later problems, which require students to worry about drawing force diagrams to scale and make sure they are consistent with the second law lead to more confusion and thus possibly less careful language. The Atwoods data seem to support this idea, in that it is probably the hardest force problem all semester, and there are no mentions of "contact force" or "gravitational force" at all; every reference but three are to "force contact" or "force gravity".

Although we need to go back and carefully listen to the audio data, our impression is that for energy, the reading problem does not seem to occur, even though in UMI, energy symbols follow the same form as the original force notation. That is, in a UMI classroom, energy is denoted by E_x, where x=k for kinetic energy, x=i for internal energy, x=c for chemical energy, etc. But we don't seem to find students saying "energy kinetic" or "energy internal", or "energy chemical". We think there are two possible explanations for that. One is that students are introduced to the different energies as early as third grade and so from early on are saying "kinetic energy", "potential energy", etc. It's possible that that language is such an ingrained habit that by the time they reach college the ideas and notation are not sufficiently different to trip them up.

In contrast, they usually don't get introduced to force at a technical level until at least high school, and even then they mostly likely learn about weight and tension and friction, rather than thinking about forces as descriptions of interactions. So all the emphasis in a UMI classroom on contact forces and gravitational forces is quite new to them and they struggle with the language a bit, especially when it does not match the symbol (as the old notation did not).

The other reason might be because of the different ontologies of energy and force. We talk about forms of energy [21] or represent it as a substance [22, 23], but we categorize the concept of force into different ontological categories (matter, or process), depending on context [24]. The more complex ontological nature of force possibly leads to more linguistic challenges for learners.

While we make no claims that helping students read symbols more effectively also facilitates their learning about forces, it is clear that the change in notation was extremely effective at solving the reading problem. Incorrect references essentially disappeared – there are no mentions of "force contact" & only one mention of "force gravity" – for seventeen problems that involved hundreds of minutes of student dialogue. However, field notes show that some students in 2015-16 felt frustrated by their constant stumbling over reading force symbols. With the change in notation, perhaps at a minimum they would simply feel more comfortable talking about force and that would facilitate their overall learning of the concept.

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