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"Force," ontology, and language

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We introduce a linguistic framework through which one can interpret systematically students' understanding of and reasoning about force and motion. Some researchers have suggested that students have robust misconceptions or alternative frameworks grounded in everyday experience. Others have pointed out the inconsistency of students' responses and presented a phenomenological explanation for what is observed, namely, knowledge in pieces. We wish to present a view that builds on and unifies aspects of this prior research. Our argument is that many students' difficulties with force and motion are primarily due to a combination of linguistic and ontological difficulties. It is possible that students are primarily engaged in trying to define and categorize the meaning of the term "force" as spoken about by physicists. We found that this process of negotiation of meaning is remarkably similar to that engaged in by physicists in history. In this paper we will describe a study of the historical record that reveals an analogous process of meaning negotiation, spanning multiple centuries. Using methods from cognitive linguistics and systemic functional grammar, we will present an analysis of the force and motion literature, focusing on prior studies with interview data. We will then discuss the implications of our findings for physics instruction.

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I. INTRODUCTION

Students' difficulties with force and motion have a long history in physics and science education research. Some researchers have observed a stable pattern of student reasoning about force and motion. Many students believe that a constant force is required to sustain constant rate motion and that when the force is removed, the object stops moving.[1–7] Reproducible patterns of reasoning such as this have been given different names such as "alternative conceptual frameworks,"[8] "misconceptions," "naive beliefs," and "naive theories,"[9] or "intuitive beliefs."[10] Students' naive beliefs about force and motion have been described as or experimentally found to be robust and resistant to instruction.[2,8,10,11] Many of these researchers have noted a similarity between students' naive models of force and motion and historical models developed by the ancient Greeks, medieval philosophers, or early physicists such as Galileo and Newton.[2,3,9,12–18]

Other researchers have noted in various experiments and/or theorized that students do not apply force concepts very consistently across a variety of problems.[6,19–26] Researchers have called this phenomenon "knowledge in pieces." These pieces have been called phenomenological primitives,[19] facets,[25] or cognitive resources.[27] These pieces of knowledge are smaller or "minimal" abstractions of everyday experiences. The knowledge in pieces model views both student reasoning and expert understanding as a dynamic process in which resources are activated by contextual cues.[28] Students explain motion and its causes by invoking different phenomenological primitives, facets, or resources depending on the context of the situation. Some of these pieces of knowledge or resources involve "force as mover"[19] or "actuating or maintaining agency."[23]

Rather than compare and contrast these two explanations any further, we will focus on two common underlying assumptions that researchers share, irrespective of theoretical standpoint.

(1) Up to now, most researchers have assumed that our human experience of motion and its causes in the physical world is a qualitatively non-Newtonian experience. Thus the physical models or resources that we extract from that experience include ideas such as "a constant force is required to sustain constant rate motion." In turn, it is generally assumed that such models or resources sufficiently account for students' confusion about force and motion when they enter their first physics course.[3–5,7,9,12,13,19,23,29–33]

(2) The second point is subtler yet pervades much of the early research. Researchers have often focused on what is different between expert physicists' reasoning and novice students' reasoning rather than looking for similarities. "Naive beliefs" researchers tend to say that students' ideas are wrong and should be confronted and replaced by "scientific" theories (see Ref. 11 for example.) Early "knowledge in pieces" researchers[19] tend to argue that students' intuitions are often correct, but their reasoning lacks the global coherence of scientific reasoning. In the spirit of the modern resources view,[28] in this paper we will explore ways in which physics students' reasoning is similar to the reasoning of expert physicists.

A. Language as a representation

Our review of the literature about the force and motion difficulty suggests that there is a great deal of agreement among all researchers about the underlying theoretical assumptions with regard to (a) the source of students' inappropriate reasoning and (b) the idea that students are not reasoning with the logical coherence of practicing scientists. In addition, many researchers notice a similarity between students' reasoning about force and motion and examples of historical theories of force and motion. This has lead to an explanation that students' difficulties, as well as the historical difficulties of physicists, stem from their similar experiences with the natural world.[3,33]

In this paper we will build on the prior research on students' difficulties with force and motion and explore how students' reasoning on this topic can appear both stable and resistant to instruction and yet fragmentary and context dependent at the same time. To better understand these seemingly contradictory data, we are going to suggest that we explore the interaction between language and cognition and the role that this interaction may play in students' reasoning about force and motion. We will suggest that students' well-documented difficulties can arise from their use and interpretation of language as well as their physical experiences and the interplay between the two.

Our main research questions are the following: (1) What role is language playing in students' difficulties with force and motion? (2) Can we gain deeper insights into student cognition with a more careful and systematic analysis of their language? To answer these questions we will begin by recognizing that language in physics functions as one of the ways of representing physical ideas.[34] Other common representations are graphs, equations, diagrams, etc. These different representations are used (a) by physicists to communicate with each other, (b) by teachers to communicate physical ideas to their students, and (c) by students to communicate their understanding to each other, to the teacher, or to an education researcher. Information theory has shown that two people need a shared repertoire and coding scheme in order to communicate.[35] From this perspective we can think of communication and learning as a process of active negotiation of meaning between the sender and the receiver rather than an act of conveying information from a sender to a receiver.[36] Our goal is to understand how language functions as part of this communication process and whether it is connected to and gives us insights into students' difficulties with force and motion. We think that a full understanding can only be achieved by examining in turn how language is used and understood by physicists, physics students, and teachers or researchers.

1. Physicists

When physicists create their theories, they must negotiate the meaning of their theories and the meaning of the language that they use to describe those theories. Some researchers have suggested that the similarity of students' naive beliefs and historical models stems from the similarity of their physical experience.

In this paper we are going to show how physicists in history engaged in a complex process of meaning negotiation with regard to the concept of force and the language they used to describe that concept. We will suggest that although they may be less sophisticated and have very different epistemological commitments, students also must negotiate the meaning of words in their physics class in order to develop understanding. Thus, if we understand what the physicists were struggling with, it may inform us about what our students are struggling with.

2. Students

When students encounter representations of ideas in the classroom, they must negotiate the meaning of those representations with their teacher and with each other.[34,37] Language is one of these representations. Researchers have pointed out that students bring their wealth of physical experiences to the physics classroom. However, students also bring with them a wealth of language conventions that they have learned. The Sapir-Whorf hypothesis[38–40] suggests that these language conventions can influence how students interpret the world. Students also have to learn the specialized meanings that physicists attach to certain words (e.g., "force") and learn the connections between their physical intuitions and those specialized meanings.[41]

There is substantial evidence that students understand the meaning of the word "force" fundamentally differently from the accepted physics definition. Data from interviews and surveys show that many students who have difficulties with force and motion treat the word "force" as equivalent in meaning to one or more of the following terms: "energy," "momentum," "inertia," "strength," and/or "power."[2,4,22,42–47] Relatively few students see "force" as equivalent meaning to a "push" or an "action."[43] It seems that many students view force as an innate property of an object rather than an interaction between two objects.[32,48]

Researchers have pointed out that the everyday usage of the term "force" in English is markedly different from the physics meaning. They suggest that these difficulties could be connected to students' difficulties with force and motion.[49–51] It has also been shown that students who can distinguish the physics meaning of force from everyday meanings do better at answering conceptual questions similar to those in the Force Concept Inventory[52] as well as numerical problems where forces are involved.[53]

3. Teachers and researchers

When teachers and researchers try to understand what students are really thinking through the medium of language (either in a classroom discussion by means of writing in an exam or talking in an interview setting), this process is also an act of meaning negotiation between student and teacher or researcher. What students mean by force and what the instructor or researcher interprets that word to mean may be two very different things. Thus we may be diagnosing a difficulty when there is none or, conversely, thinking our students have real understanding when they do not.[32,45,53–57] Likewise, if we are able to understand better what our students are saying and what they are hearing in what we say, then we may be able to understand better what they are struggling with and facilitate their learning.

Physics education researchers have suggested that students' conceptions of "force" may be reinforced by how instructors speak about force and the imagery that their language evokes.[49,58,59] As mentioned above, students often view force as an innate property of an object rather than an interaction between two objects. Researchers have suggested that locutions like "force of bat on ball"[58] and "forces *imparted* to a body"[49] encourage this idea.

Touger[59] suggested that students may "…infer that force is a concrete noun (a thing or a person) and thus an agent, that is, the doer of the action, rather than the action itself…" from locutions such as "the force acts…" or "the force pulls.…"

Schuster[57] showed that the way in which a question is asked can make a big difference to how the student responds. In an interview study, students were shown a diagram of a ball thrown straight up. A point (point A) was shown halfway up (the ball was moving up at this point). When one student was asked, "what forces are there on the ball at A?" the student indicated a force in the direction of motion. However, when the question was rephrased as "are there any other objects pulling or pushing on the ball at this moment at position A?" the same student responded, "only the Earth, downward…and…well…maybe your throw, but that was earlier, not now…though its effect is still there." It is important to emphasize that physicists consider these two questions to be equivalent in meaning.

II. LANGUAGE AND COGNITION

A. Introduction

It has been suggested that the structure of human language may reflect aspects of the human mind's organization of experience.[60] Some modern linguistic approaches that try to make explore the connections between language and cognition are "cognitive linguistics" and "cognitive semantics." Researchers from both these traditions have used linguistic or semantic methods to understand how humans understand the idea of "force."[61,62]

Probably the most complete analysis of everyday language about motion and its causes has been done by Talmy.[62] It turns out that our everyday conceptual understanding of motion and its causes is far more sophisticated (as indicated by our language) than may initially appear from studies of physics students. Our everyday language contains many elements that could be interpreted as a qualitative Newtonian model. In particular, we speak about changes in motion of one object that are initiated by other objects ("the lamp toppled because the ball hits it") or we suggest that an agent is necessary to sustain steady state motion in the presence of resistance ("the wind kept the ball rolling despite the long grass"). The concept of properties of motion that die out because of resistance to the object's motion is also well established by Talmy's analysis. (For example, a property of motion such as momentum is implicit in the statement "the ball kept rolling despite the long grass.")

While Talmy's analysis is too complex to review any further in this paper, we will use one important linguistic pattern that he uncovered in his research. In Talmy's "force dynamics," humans appear to naturally distinguish between objects that are causing other things to happen versus objects that are either simply "in the way" or having something done to them by the active object, whether its presence is implied or explicitly stated.

Johnson's "force image schemas"[61] follow a similar pattern to Talmy's ideas. Like Talmy, Johnson saw the concept of "force" intertwined with the concept of cause. He then elaborated how the concept of causation is grounded in embodied experience. For example, "the congressmen pushed the bill through congress," just as "John pushed the ball through the loop." Force image schemas are essentially an examination of the structure of causation. It appears from Johnson's research and earlier research with Lakoff[63] that the image schema of "containment" and the notion of "boundary," "in," and "out," (all aspects of our embodied experience) are fundamentally important to elaborating the idea of causation. We will use the idea of Lakoff and Johnson of containment in this paper to analyze students' conceptions of force.

Both Johnson and Talmy developed their ideas of "force image schemas" and "force dynamics," respectively, as cognitive linguistic or semantic accounts of the general human concept of causation. Thus their work extends beyond ours. Since the concept of "force" itself is intricately bound up with causation, our work will indeed use their ideas, in particular, (i) the image schema of containment (Lakoff and Johnson) and (ii) the idea of active and passive participants (Talmy). Our approach is also somewhat distinct from Johnson's force image schemas or Talmy's force dynamics. In both their approaches the authors conceptualize force as a fundamental aspect of embodied experience. Each then elaborates how the concept of force and causation is grounded in embodied experience. In contrast we will narrow our focus and explicitly consider how the word "force" itself (not the general concept of causation) is elaborated metaphorically in language. Neither Johnson nor Talmy have considered this in their work, rather treating "force" as a metonym for cause.

To analyze language and conceptual structures in physics we have incorporated ideas from systemic functional grammar into prior cognitive linguistic approaches. We will show how this combined approach may be applied productively to analyze physicists' and physics students' speech and writing.[64] We will describe this approach below.

B. Physics language is metaphorical

Lakoff and Johnson[63] suggested that human language and human conceptual system are largely made up of unconscious conceptual metaphors. We have applied this idea to physics, suggesting that physicists speak, write, and reason using conceptual metaphors.[64–66] Lakoff and Johnson defined conceptual metaphor as "systematically using inference patterns from one conceptual domain to reason about another conceptual domain."[63] Through continual usage, the meaning of conceptual metaphors can become quite literal. For example, physicists often say that "a net force causes an object to accelerate," suggesting the conceptual metaphor: *force is an agent*. When we talked to physicists, they were often surprised, at first, when we suggested that a sentence like "a net force causes an object to accelerate" was metaphorical. However, after a short discussion, they would readily admit that it is another object, not the force, which is the agent of a particular object's change in motion. Such a reaction toward unconscious metaphorical language is a hallmark of the presence of a conceptual metaphor. Conceptual metaphors are more than linguistic devices; they reflect our "embodied" experience and are used to draw inferences about more abstract domains.

C. Physicists' conceptual metaphors encode analogies

Sutton[67,68] suggested that scientists' metaphors encode analogies. We have extended this idea, suggesting that conceptual metaphors in physics encode historical analogies in the development of physics. For example, the idea of force as an agent of motion or changes in motion may be traced back to the ancient Greek philosophers who wrote about "force" as a "a world forming spirit" (Anaxagoras) or a "prime mover" (Aristotle).[69] The Greeks were making an analogy between the abstract concept of "force" and the more culturally well-understood idea of a powerful being or god who could affect change.

D. Metaphors are productive modes of reasoning

We have hypothesized that physicists' conceptual metaphors function as labels for productive modes of reasoning and/or ways of speaking about physical systems. The applicability and limitations of these conceptual metaphors are well understood by the physicists who use them.[64–66] Physicists readily admit, after a short discussion, that it is easier to just say "a net force causes an object to accelerate" rather than to talk about "the momentum transferred to an object by other objects because of the interactions between them." Thus "a net force causes the object to accelerate" becomes a productive shorthand that physicists use to talk about all the other objects that are interacting with the object of interest.

E. Ontological categories and ontological metaphors

It has been suggested that humans divide the world into ontological categories. We have shown that this idea can be applied to models in physics. The elements of a physical model: the objects or systems of objects, interaction laws, force laws, state laws, etc,[70] may be mapped to the ontological categories of *matter*, *processes*, and *physical states*.[64,66,71,72] In cognitive linguistics, Lakoff and Johnson[73] argued that all systems of conceptual metaphors have an ontological component. Conceptual metaphors often give abstract concepts an existence as concrete objects or things. For example, the sentence "a force causes the object to accelerate" suggests an ontological metaphor: *force is a living entity*.

To unite these two views and systematize our linguistic analysis, we have hypothesized that ontological metaphors in physics language are realized as *grammatical metaphors*.[64,66] A grammatical metaphor can occur when a term is given a grammatical function that does not correspond to its lexical (dictionary) meaning. These grammatical metaphors are ubiquitous in the language of physics. For example, Newton defined force (*vis impressa*) as "…an *action exerted* upon a body in order to change its state…."[74] Today, physicists readily understand the meaning of a sentence such as "a gravitational force acts on the book." Although "a gravitational force" functions as a grammatical agent in this sentence, physicists understand that this sentence describes a *process* of interaction between the book and the Earth—the meaning of the term "force" that seems to contradict its grammatical function (as a noun group) in the example sentence. Functional grammarians have suggested[75] that the elements of a sentence can be divided into *participants* (nouns or noun groups), *processes* (verbs or verb groups), and *circumstances* (generally adverbial or prepositional phrases). In order to unify the metaphorical and grammatical views, we have suggested that grammatical *participants* should be mapped to the ontological category of *matter*, and grammatical *processes* represent ontological *processes*.[64,66] (Ontological *physical states* also have unique grammatical representations but are not important for our analysis of force.) For example, in the statement "a net force causes the object to accelerate," the noun groups "a net force" and "the object" are the grammatical *participants*. They should be mapped to the ontological category of *matter*. The verb group "causes…to accelerate" is the grammatical *process* and it should be mapped the ontological *process* category. Furthermore, functional grammar naturally distinguishes between (1) *participants* that are *doing* something (either implicitly or explicitly) *to* something else (e.g., "*a force* acts," "*a force* causes the object to accelerate") and (2) *participants* that are having something *happen to* them. (For example, "object A exerts *a force* on object B," "*a force* was applied to D," "*the force* changed direction.") In case (1), "force" can be thought of as an "active" *participant*. In case (2), in all the examples, "force" can be thought of as a "passive" *participant* either being passed around or having something happen to it—agency is often left implicit or ambiguous. We have proposed that "active" *participants* may be mapped to the ontological subcategory of *living matter*; "passive" *participants* should be mapped to the ontological subcategory of *nonliving matter*.[64,66] Since physicists agree that force is *not* a living entity, force, functioning as an active *grammatical participant* (e.g., "a force acts…"), represents a *grammatical metaphor*. This mapping between grammar and ontology is beneficial in the following ways:

(1) It allows us as researchers to understand how physicists and physics students are ontologically categorizing terms and concepts when they speak. In short, we suggest that our analysis can give us a window into students' cognition.

(2) It allows us to make our analysis of language in physics systematic and reproducible. When a grammatical metaphor is identified in physics language, it represents the ontological component of the conceptual metaphors that physicists use. The theoretical framework is summarized in Fig. 1 below.

III. FRAMEWORK APPLIED TO FORCE

In this section our goal is to show how the linguistic framework just described is applicable to physicists' language about force and how it can help to tease apart the

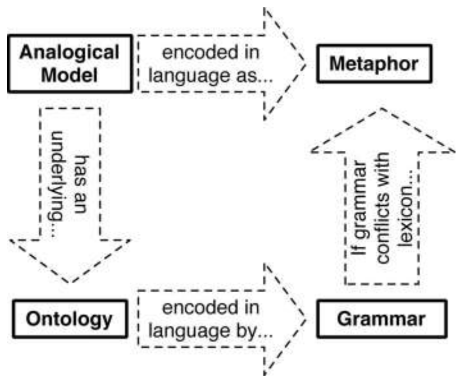

FIG. 1. A model of language in physics.

subtle meanings that may be constructed from physicists' language. We will trace the development of historical language about force by identifying underlying patterns of grammar in the metaphorical language that physicists have used both past and present. In later sections we will use the grammatical patterns we have identified to interpret students' understanding of the force concept and how it relates to motion.

A. Historical development of physicists' language about force

In our analysis of historical and modern physicists' language about force, we have identified four distinct metaphors that physicists use to describe the force concept. In the sections that follow, we will show how each metaphor is distinguished by the *location* of the force and the *role* that the force plays. While these four metaphors do not exhaust all the possible ways in which force is conceptualized, they cover the most common ways in which physicists talk about force. We also recognize that our analysis does not cover all landmark events in the conceptual development of the idea of "force," including the modern view in which many physicists view force as an extraneous concept altogether.[69] While this is an important view, we are considering the case where students are being taught about Newton's laws and therefore being exposed to an approach that includes the force concept.

1. Force is an agent

We suggest that the *force is an agent* metaphor historically became a useful way of speaking about force even though the concept of divine agency had been rejected. For example, Leonardo da Vinci wrote: "force I define as an incorporeal agency, an invisible power…"[69]. Descartes wrote: "but I desire now that you consider what the gravity of this Earth is, that is to say, *the force which unites all its parts and which makes them all tend toward its center*…[our emphasis]."[69] In modern times, physicists often say or write "a force acts on an object" or "a net force accelerated the object."

From the examples, we may observe the following pattern:

(1) *Role.* If we examine all the examples shown above (from da Vinci and Descartes to modern physicists) we can see a common grammatical structure. In each case, the term "force" is functioning as an active grammatical *participant*, an object that is doing something to another object (grammatical *participant*). For example, "*the force*…makes them all tend toward its center."

(2) *Location.* Prepositions such as "on" suggest that the force is *external* to the object(s) that it is interacting with.

2. Force is an internal desire or drive

This metaphor has two separate themes that emerged during the middle ages. The first theme represents purely a way of talking about how objects interact. The second theme was seriously entertained as a theory during the middle ages. The first theme is based directly on Plato's philosophy of attraction and repulsion. For example, Copernicus wrote: "I think that gravity is…a certain natural appetition [desire] given to the parts of the Earth by divine providence of the Architect of the universe…."[69]

Although Kepler explicitly rejected the idea of force as an internal desire in a literal sense, his writings are still peppered with the metaphor. Kepler wrote in the early 1600s: "gravity is a mutual affection among related bodies which tends to unite and conjoin them."[69]

The second theme is the impetus model of motion, formulated by Buridan and others. As an example of the second theme, consider Buridan's writing: "…he [God] has given to each of them [the celestial spheres] an impetus which kept them moving since then…."[69]

Nicholas of Cusa: "the child takes the [spinning] top which is dead…, without motion, and wants to make it alive…The spirit of motion, evoked by the child, exists invisibly in the top…[When] the spirit ceases to enliven the top, the top falls."[69]

This line of language is almost nonexistent in the language of modern physics. However, a metaphorical and grammatical analysis of this language is essential for our understanding of students' reasoning. An analysis of the examples from both themes reveals a common pattern:

(1) *Role.* Our analysis is identical to that described above for the *force is an agent* metaphor. In each case, the "force" (referred to as "appetition," "affection," "impetus," or "spirit") functions as an active grammatical *participant* that drives the object to action.

(2) *Location.* In addition, each of the statements above contains a clear clue as to the location of the force. In each case, the force appears to reside inside the object that is moving or spinning. Words such as "given to" and prepositions such as "in" indicate the presence of the force *inside* the object.

Thus to identify the presence of the *force is an internal desire or drive* metaphor we must identify both force functioning as an active grammatical *participant*, *and* the presence of a conceptual container metaphor that suggests that the force is either inside the object or a property of the object. Words such as "given to," "in," "inside," "of," and possessive case (e.g., the object's force) will be used to identify the container metaphor.[63]

3. Force is a passive medium of interaction

This line of reasoning is historically the most complex and we shall only provide a cursory analysis here. This metaphor encompasses all cases where the motion or changes in motion of one object are interpreted as being caused by the action of another physical object rather than a force. In turn, force functions to elaborate the causal mechanism of the interaction. The mechanism of interaction takes two basic forms.

The first form is grounded in an analogy to a disturbance in a medium. (Namely, the ancient Greek idea that the effect of the moon was transmitted by the Earth's atmosphere.) In this line, Bacon wrote about force as a "species," a disturbance in a corporeal medium that pervaded all space. This idea was taken up by Descartes, Hooke, and Euler, who all proposed ethereal models to explain how one object could exert an influence on the other at a distance.

The second form is the metaphor that "force" is some sort of passive substance that is exchanged between two objects. For example, Newton began his definition of impressed force thus: "an impressed force is an action exerted upon a body…."[69] This definition is interesting because Newton clearly defines the ontological status of impressed force as a *process*, yet force is functioning as a passive grammatical *participant*. The process by which verbs and verb groups are turned into nominal groups in scientific language is discussed in detail in Ref. 76. In modern language, physicists say "object A exerts or applies a force on or to object B." In this language force functions in the same sense as "paint" in the sentence, "I applied paint to the wall." The *process* nature of the term "force" contradicts its grammatical function, i.e., a grammatical metaphor is present.

From the examples, we may observe the following pattern:

(1) *Role.* "Force" functions grammatically as a passive *participant*. It is something that is being passed by one object to another. The force does not directly do anything to any other participant on its own. In our coding scheme linking grammar to ontology, "force" is mapped to *nonliving matter* in such cases.

(2) *Location.* In the example, "object A exerts or applies a force on or to object B," the force is external to the two objects. This is suggested by the prepositions "on" and "to." Both prepositions suggest the force makes contact with the surface of object B but do not suggest that the force metaphorically goes inside object B.

4. Force is a property of an object

The fourth and final usage of the word "force" in physics is one where force is spoken about as a property of an object (identified by the presence of the container metaphor), but functions as a passive grammatical *participant* rather than an active one. This metaphor emerged last in the historical development of physicists' language about force. Newton defined force as both an *action* (impressed force) and also as property of motion (*vis insita* or force of inertia). Leibniz also wrote about force (*vis viva*) as a property of motion. For example, "…two soft or unelastic bodies meeting together lose some of their force…."[69] In the original French version of this letter, Leibniz[77] referred to this force as *forces actives* or simply *force*.

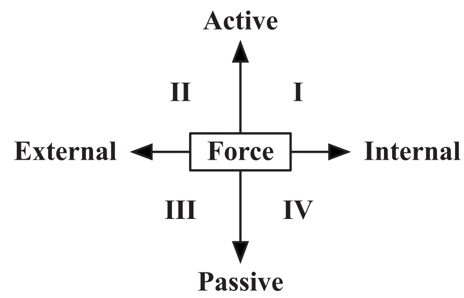

FIG. 2. Dimensions of physicists' language about force.

From the examples, we may observe the following pattern:

(1) *Role:* "Force" functions as a passive grammatical participant.

(2) *Location.* The force may be interpreted metaphorically as a property of the object due to the presence of a container metaphor. In Leibniz's example, this is identified by the presence of "their force," suggesting that the force belongs to the bodies Leibniz is speaking about.

Language such as that displayed by Leibniz lasted a remarkably long time in the history of physics. Despite attempts[74] to disambiguate "force of inertia" (*vis insita*, *vim motricem*, or *vis inertiae*) from "living force," (*vis viva*, *force vive*, or *force actives*) these terms were still present in the mid-19th century. Joule still used the term *vis viva* in his writings in 1840, and Helmholtz's seminal energy conservation paper of 1847 was entitled "Über die Erhaltung der Kraft" (On the Conservation of Force).[78] Today, physicists reserve the word "force" for Newton's *vis impressa* but still frequently talk about force as a property of an object, for example, "the tension *in* the rope" or "the weight *of* an object." Such prepositional phrases indicate the presence of the metaphor *force is a property of the object*.

B. Discussion

1. Four metaphors

What we realize from this analysis of how the four force metaphors emerged is that we can separate physicists' language about force along two orthogonal dimensions with each of the four metaphors falling into one of four quadrants (see Fig. 2 and Table I). The two dimensions are (1) the *location* of the force [either *internal* or *external* to the object(s) concerned] and (2) the *role* of the force as either an *active* object or a *passive* object. The *location* of the force can be identified by a metaphorical analysis, considering the presence of prepositions such as "in" and "of" (container metaphor=internal) or "on" and "to" (surface metaphor =external), while the *role* of the force is identified by how the force functions grammatically in a sentence (active or passive *participant*). A summary with examples is shown in Table I.

2. Refining ontological categories

One final key point needs to be made about this analysis of the historical development of force concepts and the cor-

TABLE I. Summary of the four metaphors and examples of historical and modern usage in language.

Quadrant	I	II	III	IV
Metaphor	Force is an internal desire or drive.	Force is an agent.	Force is a passive medium of interaction.	Force is a property of an object.
Historical examples	Kepler: "Gravity is a mutual affection among related bodies which tends to unite and conjoin them."	Da Vinci: "Force I define as an incorporeal agency, an invisible power…."	Newton: "An impressed force is an action exerted upon a body…."	Leibniz: "…two soft or unelastic bodies meeting together, lose some of their force…."
Modern language examples	The moon is attracted to the Earth.	A force causes an object to accelerate. A force acts on an object.	Object A exerts or applies a force on or to object B.	The tension in the rope. The weight of an object.

responding development of language used to describe the concept of force. To make this point we must make the distinction between the definition of a physical quantity such as acceleration $\vec{a}=d\vec{v}/dt$ and a causal relation that relates physical quantities to each other.[70] An example of a causal relation would be Newton's second law that relates the physical quantities of acceleration and mass into a causal relation: $\vec{a}=\vec{F}_{\text{net}}/m$. In the historical record that we have presented, both $F=mv$ and $F=mv^2$ were written down (often in words rather than symbolically; here F stands for *vim motricem* or *quantitate motus* and *vis viva*, respectively); however there is no indication that $F=mv$ and $F=mv^2$ were written as a causal relations. All the evidence (apart from Buridan himself) presented above shows that physicists were trying to write down the definition of a physical quantity or property of motion. Clagett[79] agreed with our interpretation. In an extensive historical analysis of mechanics in the middle ages, he concluded that impetus underwent an ontological shift from a cause of motion to an effect of motion sometime between the late 16th century and early 17th century (around the time of Galileo). In our model (Fig. 2), this is a movement from quadrant I to quadrant IV.

Taking a broad overview of history, we observe the concept of force moving from causing motion to an effect of motion or a quantity of motion. We see new concepts of force being introduced (*vis impressa*) when a new distinction needed to be made. It is only rather recently in the history of physics that the concepts of kinetic energy and momentum were separated out from the "force" category and been given their own distinct names rather than being referred to as types of force.

We suggest that our analysis has uncovered a prototypical example of a central cognitive activity in physics that has not had sufficient attention paid to it in the research literature. Historically we see physicists engaged in trying to define and refine the meaning and ontological status of the term "force" in their descriptions of motion and its causes. We term this activity "ontological disambiguation."

IV. STUDENTS' DIFFICULTIES WITH FORCE AND MOTION: AN EXAMPLE OF ONTOLOGICAL DISAMBIGUATION

This historical analysis may inform us about how our students are thinking about force and motion. Traditionally education researchers have taken students' reasoning about force and rewritten it as a causal relationship either as $F_s=\alpha v$, where F_s denotes the "supply of force" and α is a constant of proportionality,[46] or as $F_{\text{net}}=mv$.[80] They then proceed to show that this relationship leads to incorrect predictions about the motion of objects.[80] We wish to propose an alternative view. In Table II we have placed, side by side, the words of students and the words of some of the famous players in the development of mechanics.

The remarkable similarity (between students and the historical figures) of the statements compared in Table II was a pivotal moment in our research process. Appreciating what Newton and Leibniz were struggling with prompted us to begin to question whether we had fully understood what our students were struggling with when they made such statements. We suggest that some students are engaged in an analogous act of ontological disambiguation. We will use "ontological disambiguation" to mean any struggle to define and ontologically categorize the meanings of physical terms including their context-dependent role describing a physical theory. We wish to hypothesize the following.

A. Hypothesis 1

Many students who appear to have the force and motion difficulty are well aware that motion continues undiminished (without any internal or external intervention to sustain the motion) when all external resistance is removed. In their doctoral dissertations, Driver,[8] Tasar,[82] and Yuruk[83] all presented examples of this from student interviews. Elby[21] noted this point anecdotally. Anecdotally, we too have both observed this apparent conflict in our students. We suggest that many students do not believe that a force is needed to sustain constant speed motion. As we showed in Sec. I, re-

TABLE II. Comparison between inventors of mechanics and modern students.

Student	Physicist
"A force of inertia," "the power also has a force."[a]	"The *vis insita* or innate force of matter is a power of resisting…" (Newton)[b] "…this *vis insita* may, by a most significant name, be called *vis inertiae* or force of [inertia]." (Newton)[c]
"I mean the weight of the ball times the speed of the ball…. Momentum is…a force that has been exerted and put into the ball so this ball now that it's traveling has a certain amount of force…."[d]	"Bodies of equal weights and moved with equal velocities have equal forces…." (Galileo)[b]
"…a combination of the velocity and the mass of an object. It's something that carries it along after a force on it has stopped…. Let's call it the force of motion…."[d]	"…mathematicians…estimate the motive force by the quantity of motion or by the product of the mass of the body into its velocity." (Leibniz)[c]
"I understand that [friction and air resistance] adversely affect the speed of the ball…they sort of absorb some of the force that's in the ball…."[d]	[Talking about a pendulum] "…a body falling from a certain height acquires a force sufficient to return it to the same height…unless the resistance of the air and other slight obstacles absorb some of its strength…." (Leibniz)[c]

[a]Reference 2.
[b]Reference 69.
[c]Reference 74.
[d]Reference 81.

searchers have observed that students see force as an "innate property" of an object. We are suggesting that many students have a notion of impetus as an *effect* or *property* of motion rather than a cause of motion. Thus students' reasoning is perfectly consistent with a Newtonian conception when they suggest that there is a force in the direction of motion if we understand that they are talking about a force of motion (i.e., momentum or energy) rather than an impetus necessary to sustain motion.

B. Hypothesis 2

The historical analysis presented above is a typical example of ontological disambiguation and should serve as a model for the same struggle that our students are having. Some students may neither possess a model in which a force is needed to sustain a constant rate motion nor be applying a "force as mover" p-prim in certain contexts. These students may simply be struggling to disambiguate cause and effect relationships, struggling to decide what to call a "force" and struggling to understand when (if ever) it is appropriate to talk about force as a cause of motion or an effect of motion. Both the stubbornness and the context dependence of the force and motion difficulty are accounted for by the ontological disambiguation view.

V. STUDENTS' DIFFICULTIES WITH FORCE AND MOTION: A NEW LOOK AT OLD DATA

A. Introduction

We will test hypothesis 1 against a large body of interview data that has been published over the last 30 years. Students' difficulties with force and motion are probably one of the most studied student difficulties in science education. Traditionally researchers have interpreted students' reasoning as indicating a belief that a constant force is required to sustain constant rate motion.

If our idea that students see force as a property of motion rather than a property of the object necessary to sustain motion is correct and we assume that a metaphorical or grammatical analysis of their language can reveal what they are really thinking, we predict that if we analyze students' reasoning about force and motion, most will fall into quadrant IV of Fig. 2 rather than quadrant I. If students are recruiting Buridanian ideas, then they will fall into quadrant I. If students are recruiting Aristotelian ideas, their reasoning should fall into either quadrant II or III. (Aristotle's idea of forced motion required an external agent to sustain motion, e.g., the air behind the flying arrow.)

B. Method

There are many papers published those document students' difficulties and present examples of "typical" student responses in interviews. In this study we followed the following methodology. We gathered as many research papers as we could find on students' difficulties with force and motion. We used two methods of search. The first was a research database search in ERIC and google scholar. The second was to use physics education research resource letters such as that in Ref. 84. We narrowed our sample to 12 papers or books that contained codable transcripts of student reasoning about force and motion.[2,3,6,8,14,16,46,47,81,85–87] Most importantly we only chose examples where students were claimed (by the researchers) to have the standard force and motion difficulty, namely, that a constant force was necessary to sustain constant rate motion.

We coded students' explanations of their reasoning into one of the four quadrants of Fig. 2 using the methods we have already developed.

1. Role

The *role* of the force was coded as follows: the force was coded *active* (causing or sustaining) the motion when the following occur:

(1) Force functioned as an active grammatical *participant*. For example: "the *force* is keeping the object moving," "the *power* makes it go," "the *force* is moving it on," "the *energy* produces action," or "the *force* acts…."

(2) Any obvious suggestion that the force was necessary for the object to move, that motion was a result or consequence of a force. For example, "*if* there is no force *then* it cannot not move"; "the force is zero *therefore* it stops." The presence of words such as "if, then, therefore, because," etc., are the essential cues.

The force was coded *passive* (an effect, property, or result of motion) when the following occur:

(1) Force functioned as a passive grammatical *participant*. For example, "the *force* in the object dies out," "the *car's force* switches direction," "the *power* has stopped…," "friction absorbs the *force* in the ball," and "the object loses or expends some *force* as it plows through the air."

(2) Force was spoken about as a result or consequence of motion. For example, "the object is no longer moving *so* the force is zero," "the velocity is constant *so* the force is constant," and "there is no force *because* the object has stopped."

If the role of "force" was unclear or ambiguous, we coded it "ambiguous." There are two possible cases:

(1) Functional grammarians Halliday and Martin[76] suggested that structures such as "as the force decreases and the car slows" denote two concurrent events. The cause-effect relationship is ambiguous. There is no "if-then" structure or conjunction such as "so" that denotes one resulting from the other. Such cases were coded ambiguous because of insufficient evidence of the role of the force in relation to the accompanying process.

(2) Students sometimes used a confusing mix of *active* and *passive* in the same paragraph.

2. Location

The *location* of the force was coded as follows: clear evidence that the force was *inside* the object or a *property of* the object was coded as "internal." Clear evidence that the force was *external* to the objects, being passed around in some way, was coded "external." Cases where the location of the force could not be reliably identified were coded "ambiguous."

C. Results

Out of 49 student explanations gathered from 12 different studies, spanning 34 years, the *role* of the term "force" was coded as follows: 33% of explanations were coded *active*, 47% of explanations were coded *passive*, and 20% were ambiguous. Out of the same 49 explanations, *location* was coded as follows: 6% coded "external," 27% coded "internal," and 67% of the statements left the *location* of the "motion force" ambiguous. Inter-rater agreement was 100% after discussion.

D. Discussion

The key finding from coding the transcripts is that a majority of students (47%) showed a conception of the "motion force" as a passive participant in the events rather than an active mover. Indeed, some students may be activating a model in which a "motion force" is needed to sustain a constant rate motion in the given circumstances, however the majority of students do not display such reasoning in the examples we studied. This result supports our hypothesis that many students, similar to the historical physicists, are conceiving of force as a property of motion rather than an impetus that is necessary to sustain motion.

VI. CASE STUDIES

We will consider two case studies drawn from two different Ph.D. dissertations. Through an examination of these case studies, we will show how reinterpreting students' difficulties with force and motion as a problem of ontological disambiguation (hypothesis 2) helps us to understand their reasoning better. In both these cases, students appear to be interacting with each other and with the researcher in an environment that seems to promote open discussion, sense making, and ontological disambiguation.

A. Case study 1

We will use this case study to show that a student's seemingly incomprehensible reasoning is, in fact, quite reasonable if we recognize the student's difficulty as one of ontological disambiguation rather than a fundamental misconception or as a misapplication of a context-dependent p-prim.

Tasar[82] recounted an example of a discussion with a student concerning the force and motion misconception. "F.T." is the author and "June" is the student.

The interviewer asks June what motion would be like in a frictionless environment:

FT: If there wasn't friction how do you get things move?

June: You just have to like initiate motion and then it just continues.

FT: You still need a force?

June: Yeah. I think so I mean it's not just gonna move on its own, you have to start it. Something it has to act on the mass to make it move.

FT: and if there is no friction what will be the speed of that object?

June: It is gonna be constant.[82]

Note that June never mentions the word force. She clearly understands that an agent is needed to initiate the motion of an object. She also seems to think that the object will keep moving at a constant speed without external or internal intervention. Her understanding appears to be qualitatively Newtonian. This interpretation is further corroborated by her comments below.

The interviewer gives a concrete example of pushing a chair on ice, considering that ice is close to a frictionless surface:

FT: …and what would be the subsequent motion after I take my hands off it?

June: I think, if there is no friction it is just gonna keep going.[82]

June appears to understand that once you stop pushing the object it simply keeps going at a constant speed. The interviewer has clarified that her hands are no longer touching the chair so it is clear that June believes nothing is needed to keep the chair going. Minutes later the interviewer rephrases the question about an object on a frictionless surface to June:

FT: Okay. If there is no force, what would be the speed? If there is no force, that means?

June: It is gonna stop?[82]

Based on June's final response, Tasar suggests that June has gone back to the "motion implies force" misconception. diSessa and others pointed out that such examples are evidence for the locality and contextual dependence of students' knowledge and reasoning in physics.[19,21]

We wish to propose a different interpretation of the transcript quoted above. Until the final excerpt, June appears to understand that another object needs to interact with the object of interest to "initiate (the) motion" of that object. Once that interaction has ceased, motion continues unabated. It appears that only once the interviewer invokes the term "force" that June appears non-Newtonian in her reasoning. However, according to our hypothesis, if June believes that the word "force" refers to a property of an object's motion (roughly synonymous with momentum) then June's responses are totally consistent. If an object has no momentum, which means it is not moving. Hence June's final uncertain response: "It is gonna stop?" It may be plausible that a student can reason inconsistently from 1 min to the next without being aware of it. However, another plausible explanation is that June believes that her two answers are consistent. Our linguistic interpretation of the force and motion difficulty provides the key to this consistency. June is confused between the dual ontological statuses of force as an interaction between two objects (Newton's *vis impressa*) versus force as a property of motion (Newton's *vis inertiae*). Or rather she has not made this distinction clear in her understanding. Our interpretation is that June has no misconception at all. She only has a difficulty understanding the specialized meaning of "force" as physicists use it. The context dependence of her responses reflects the necessary process of ontological disambiguation and refinement

B. Case study 2

In her dissertation, Yuruk[83] presented interview transcripts and journal entries from a group of students who were required engage in activities such as "poster drawing, journal writing, group debate, concept mapping, and class and group discussions." The activities of her experimental group were aimed at getting students to engage "metaconceptual knowledge and processes." It was hypothesized that by being aware of their past beliefs, monitoring their understanding, and evaluating the plausibility and usefulness of their conceptions, they would learn physics better and develop a deeper understanding than a control group that did not engage in such metacognitive or monitoring activities. Apart from the initial poster activity described below, students did not appear to have been explicitly asked to analyze their language about force.

We will trace the progress of one of Yuruk's subjects (Lisa). Initially Yuruk diagnosed Lisa as having the force and motion misconception although it appears to us (from the transcripts that Yuruk presents) that Lisa is qualitatively Newtonian in her understanding. She is aware that an object on a frictionless surface keeps moving at a constant rate without outside or internal intervention. (Rather similar to the case of June shown above.)

At some point near the start of the intervention, students were required to make a poster about their understanding of the term "force." Lisa described her understanding of the meaning of force as "like energy being applied to an object."[83]

As Lisa's understanding of Newton's laws developed, she reflected in a journal entry: "The main difference in my initial and current ideas is the idea that inertia is a force. I said that there was a force if the object was moving even the applied force was long gone."[83] Note that she does not suggest that this inertia is making the object move.

In another journal entry, Lisa reflected:

I said a force is motion and therefore an object after being pushed still has my definition of force. *If you define force as an interaction my statement is wrong. It's all a word game.* What I thought of as included in my definition of force, Newton called inertia. Newton's definitions and laws better explain motion. *It divides my definition of force into different groups based on what happens to the objects* [our emphasis].[83]

Note how Lisa's distinction between inertia and force is identical to Newton's definitional distinction between *vis inertiae* and *vis impressa*.[74] Lisa's trajectory toward understanding provides clear evidence that language and ontological categorization are at the heart of her learning about force and motion. From the transcripts of Lisa's discussions and her journal entries, we see that her learning about force is best described as an act of ontological disambiguation rather similar the though processes of the physicists analyzed in the section above. Other students in Lisa's experimental group presented similar reflections that suggest that ontological disambiguation of language was playing a big part in the development of their understanding.

C. Discussion

We have presented examples of two already published case studies of students struggling with the ideas of force and motion. Our hypothesis is that some students are having difficulty understanding the ontological status of the force concept in physics. More specifically, they are struggling to disambiguate limitations and applicability of force and/or other objects as causes of changing motion of a particular object from force as an effect or property of motion in much the same way as physicists did in the historical development of force and motion concepts. The two examples we have presented support our hypothesis and show how students' reasoning may be understood better through the lens of ontological disambiguation. Students' difficulties and the apparent context dependence of their reasoning are both explained by the ontological disambiguation hypothesis.

VII. DISCUSSION AND IMPLICATIONS

The evidence we have presented supports our hypotheses that (1) students view force as a property of motion rather than a "sustainer" of motion and (2) learning about force involves an act of ontological disambiguation where students have to refine their understanding of what the term "force" means in physics.

Our linguistic analysis has provided us with deeper insights into how students reason about force and motion. If grammar and metaphor correctly reveal what students are thinking, then only a minority of students appear to have a Buridanian impetus model of force and motion, while the majority of students have a conception of force as a property of motion, similar to the understanding of Galileo, Newton, Leibniz, and others. We believe that our students might come into their physics course with a qualitative view of motion similar to that of Newton and others but have not yet made the ontological distinction in language between properties of motion (such as inertia, momentum, and energy), referred to as "force" and Newton's *vis impressa* or impressed force. Much of what we have found students to be struggling with may fit well with the "coordination" model of conceptual development.[88]

Understanding our students better

We suggest that in many cases, when a student puts in the "force that my hand gave it" into the free body diagram for a projectile, he or she is asking the instructor the following: "What should I call 'force'? Is it a property of the object's motion or an interaction? Does it quantify something about the interaction between two objects or does it quantify a property of the object?" And then under the category of properties, "does it quantify some *activity* of the object (what we would call, with hindsight kinetic energy) or does it quantify a property of the motion? (What we now term momentum.)" From this metaphorical point of view, students' confusion is hardly a misconception, but an analogous struggle to refine and define terms, to build on their experience and refine their every day language in the context of learning physics. From the historical point of view, the difficulty of this struggle cannot be underestimated and may go a long way to explaining the stubbornness of these "misconceptions." After all, if we as teachers are not answering the real question students are asking, how can we expect our students to figure it out? In summary, part of student learning is an act of negotiation of meaning between the instructor and the student.

In this paper we have shown that the combination of grammar, ontology, and metaphor can reveal underlying patterns of consistency in physicists' language. This linguistic framework can also explain why students struggle so much with certain ideas and why many so called "misconceptions" are so "resistant to instruction." In summary, physicists' language indicates that they categorize the concept of "force" into different ontological categories, depending on context. In the case of ontological disambiguation, we, the teachers, may simply be failing to hear the questions our students are asking. Namely, students need help sorting out the different ways in which the concept of force is categorized ontologically rather than help being disabused of certain mistaken ideas they might have.

We can make no claim that this approach accounts for all student difficulties or even accounts for all instances of a particular difficulty. It is quite possible that some fraction of students who ask "should I include the force my hand gave it?" are asking an ontological question, as we suggest, while another fraction of students have an impetus model in which force is necessary to sustain motion. But we want to suggest that this approach opens up a whole new dimension of understanding of what our students are thinking. In many cases it can help us recognize and answer students' questions in a different and possibly more appropriate way. In many cases our framework can help us account for much of both the inherent stability of students' responses to a given situation and the contextual dependence of their reasoning and apparently fragmentary nature of their ideas. If learning physics involves learning to *represent* physics, then learning physics must involve a refinement of terminology and cases in language. And part of the teacher's role in the classroom must be to support that learning process—something that we, as teachers, are often unaware of.

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