Drawing on force ideas for kinematic reasoning in introductory physics

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In this paper, we identify some of the connections students make between force ideas and kinematics concepts, in their responses to kinematics questions. We coded 887 written responses to three different kinematics questions and identified patterns where students draw on force to make sense of kinematics concepts such as acceleration, velocity, and trajectory. We found that students draw on force frequently, in addition to other kinematics reasoning, in resourceful and context-dependent ways. Our findings suggest that instruction may be able to productively make use of students' understanding of force to support kinematics learning.

2023 PERC Proceedings edited by Jones, Ryan, and Pawl; Peer-reviewed, doi.org/10.1119/perc.2023.pr.Huynh

I. INTRODUCTION

Prior work has studied student understanding of forces and kinematics, showing that the two concepts are strongly related and support each other in university introductory physics contexts. Extensive research has identified patterns in student understanding of force and kinematics through various lenses, including naive beliefs and misconceptions [1-2], difficulties [3-5], knowledge in pieces [6, 7], and conceptual resources [8, 9]. Regardless of the approach, research tends to agree that students come to physics class with prior sensory experiences of force and motion, although their conceptualization of force might not be aligned with current physics models. However, instructors' stances towards students' understanding of force and motion—i.e. whether students' ideas are robust and resistant to instruction [10] or they are potentially productive and context-dependent [8,9]—inevitably influence instructional perceptions and design [11, 12] around the two concepts in physics courses.

Traditional introductory textbooks and curricula often teach kinematics before forces (see [13-15], for example). In this approach, acceleration is taught from a kinematical perspective before introducing its mathematical relationship with force. Then, when force is introduced via Newton's 2nd Law, force is presented mathematically as something that produces acceleration. There are fewer approaches where force is introduced qualitatively or even quantitatively before the presentation of kinematics (see [16], for example). These latter approaches introduce forces first, and then introduce acceleration as the result of an imbalance of forces. An instructor's choice of approach might depend on their instructional goals for student learning. For example, when instruction focuses on solving kinematics questions using definitions and graphical representations, instruction might postpone—and even discourage—the use of force ideas. There is little research on the relative effectiveness of a kinematics-first vs. a forces-first approach to instruction, with the exception of [17], which found that there were no differences in conceptual and attitudinal survey outcomes between the two approaches.

Our study builds on [17], contributing to this body of work from a slightly different angle. We take a resources approach [6,7] to identifying ways in which students draw on force reasoning to productively sense-make about kinematics questions. We analyzed student responses to kinematics questions that did not specifically call for force reasoning to (i) get a sense of how frequently students use force ideas in kinematics contexts and to (ii) characterize some of the ways in which students draw on force reasoning to support kinematics reasoning. We found that even without prompting, students often draw on ideas about forces in their responses as they think about acceleration, velocity, and trajectory, in addition to using other kinematics information including graphs, diagrams, vectors, and mathematics equations. Our findings suggest that force ideas can be conducive for student understanding of kinematics, implying that it is worth considering instruction that does not discourage force reasoning in kinematic instruction.

II. THEORETICAL FRAMEWORK: RESOURCES

In resources theory, a resource is a piece of knowledge that is activated in context-sensitive ways, sometimes in concert with other resources, to form an idea, explanation, argument, or theory [7, 12, 18-24]. Researchers have theorized extensively about the development, structure, and role of resources, and have used resources theory to highlight the dynamic, emergent, complex-systems-like nature of student thinking.

Our work draws extensively from resource theory's orientation toward student thinking as fundamentally sensible and continuous with formal physics [6, 12, 18-20, 22, 24], seeking to make apparent the continuities between students' thinking and formal physics, even and especially when that thinking does not use the language of formal physics or is canonically incorrect. Our work also takes up resource theory's definition of learning, which involves changing the structure or activation of resources, by reorganizing, refining, or increasing the degree of formality of resources [6, 20-23]. Our primary aim in identifying resources is to provide instructors with knowledge that they can use to build from student ideas in instruction.

III. RESEARCH CONTEXT AND METHODS

A. Context

The resources we report here were identified in written student responses to three kinematics conceptual questions: the Ball-on-ramp, the Oval track, and the Comet questions. All three questions included diagrams (shown in Fig. 1) and asked for student reasoning about the objects' velocity and acceleration at specific points along the trajectories. For example, the Oval track question showed students the top-view diagram of a car moving at constant speed along an oval track and asked students to draw vectors to represent the velocity and acceleration of the car at points A through F and explain their reasoning.

We chose these questions because they are questions or modified versions of questions that have previously been used in studies that investigate students' kinematics ideas from different theoretical lenses. Student can use kinematics rules to infer the object's velocity and acceleration in each of these scenarios, for example by finding the displacement or by subtracting velocity vectors, respectively. However, we found that student responses frequently included connections to force to make sense of the kinematics concepts, even though unprompted by the questions.

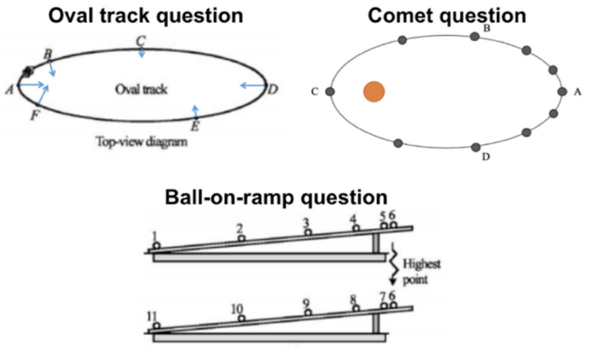

FIG. 1. Diagrams for questions used in our study. The Oval track and Ball-on-ramp diagrams are reproduced from prior work [25].

We analyzed a total of 887 written responses from introductory physics courses at four US colleges and universities. Three of the four institutions are in the Pacific Northwest; one of them is a large public university, one is a small private university, and the other is a mid-size community college. The fourth institution is a large public university on the East coast. The racial and/or ethnic demographics for the colleges/universities in our study versus all college/university students are shown in Figure 2. Figure 2 suggests that the institutions in our study are not racially and/or ethnically representative of the population of college-bound freshmen in the US. By this measure, the universities in our study serve more Asian and Asian American students, fewer Hispanic or Latinx students, fewer Black or African American students, fewer multiracial students, and fewer white students than the general population of college students. The median parental income of the students at colleges/universities in our study is also higher than the national average. This sampling limits the generalizability of our results; though the resources we identified are common among the students in our sample, we cannot speak to their commonality in the population of introductory physics students writ large.

B. Method

To identify how students in our sample used force ideas to reason about kinematics concepts, we conducted a preliminary coding of student responses to the three questions. First, we made note of every statement that included a force idea and a kinematics idea. Then we built a coding scheme [27] to consistently identify the kinematics concepts that students name in relation to force across the three questions. We found that among all kinematics concepts, the three concepts that were most frequently connected to force were acceleration, velocity, and trajectory of motion.

Using the coding scheme, authors TH and AA then independently coded 20% of students' responses, first identifying whether a response included a force idea (yes/no). If the response included a force idea, we coded for the kinematics concepts that students connected force ideas to, if any, including acceleration, velocity, and trajectory. We measured inter-rater agreement using the normalized difference between the total number of possible codes and total number of disagreements because our codes are not mutually exclusive [28, 29]. The percentage agreement was 98.2%. Disagreements were resolved through discussion, resulting in a modified coding scheme which author TH used to code the rest of the data set. Lastly, author TH used each set of responses coded with force ideas (forces connected to acceleration, forces connected to velocity, and forces connected to trajectory) to identify emergent patterns in the ways that forces ideas were used resourcefully to reason about these kinematics concepts.

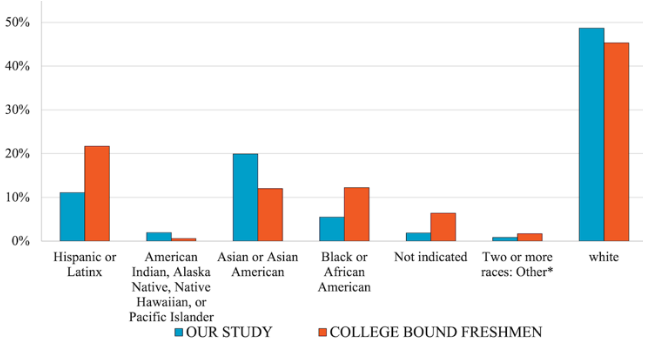

FIG. 2. Racial and/or ethnic demographics of institutions in our sample (blue) versus all college-bound freshmen (orange). Blue bars were constructed using demographic data provided by offices of institutional research or institutional websites, weighted by sample size. Orange bars were constructed using data from Kanin and Cid [26].

IV. RESULTS AND DISCUSSION

A. Force ideas are prevalent in kinematics sense-making

We found that students frequently used force ideas to reason about the three kinematics questions in our data set (Table I). Oftentimes, students linked force ideas to more than one kinematics concepts, resulting in the assignment of multiple codes to a single response. Other contextual factors, including class-size, instructional styles, formal and informal exposure to force concepts, and lived experiences with force ideas, may impact the prevalence and particularities of students' use force ideas; however, we do not have sufficient information to formulate specific claims about the influence of specific contextual factors.

Though not the focus of this paper, we found that students often drew on force reasoning in concert with reasoning with kinematics definitions and representations, including graphs, vector diagrams, etc. For example, a response to the Ball-on-ramp question stated:

"When the ball is rolling up the ramp, it is slowing down. This is because the direction of the acceleration is opposite to the direction of motion of the ball. Because of this, the velocity vectors are getting smaller. [...] The acceleration

has a constant magnitude throughout because the acceleration acting on the ball is the acceleration due to gravity. This is 9.8 m/s^2 and does not change."

In this response, a student used the relative direction of acceleration and motion ("opposite") to explain why "velocity vectors are getting smaller," demonstrating conceptual understanding of multiple kinematics concepts, including the vector nature of velocity and acceleration. Then they specifically referred to gravity as the reason for the constant value of acceleration (underlined). This is an example of how drawing a force idea can complement—rather than hinder or replace—student kinematics reasoning.

TABLE I. Prevalence of force ideas in responses to kinematic questions (Force, F-A, F-T, F-V are codes that identify a force idea and connect forces with acceleration, trajectory, and velocity respectively).

Question	Ball-on-ramp	Oval	Comet
N	327 (100%)	271 (100%)	289 (100%)
Force	123 (37.6%)	29 (10.7%)	95 (32.9%)
F-A	91 (27.8%)	16 (5.9%)	71 (24.6%)
F-T	35 (10.7%)	19 (7.0%)	17 (5.9%)
F-V	45 (13.8%)	6 (2.2%)	32 (11.1%)

B. Drawing on force ideas to reason about acceleration

Among all kinematics concepts in our data, students in our sample drew on forces more frequently when reasoning about acceleration than when reasoning about trajectories or about velocity (Table I). Sometimes they connected force ideas to reasoning about the magnitude of acceleration, other times to its direction.

1. Force causes acceleration

The resource "force causes acceleration" is identified when students name a causal relationship between force and acceleration. Oftentimes, students' responses include phrases such as "acceleration due to force" or "force that causes acceleration", signaling this resource. For example, a response to the Ball-on-ramp question stated:

"[...] The direction [of acceleration] can be easily explained by gravity. Gravity is always down and since that is the only outside force on the ball it is the only thing causing acceleration."

In this response, the student determines the direction of acceleration by drawing on the idea that "[gravity] is the only thing causing acceleration." Here, it is in identifying the force first that the student correctly characterizes the acceleration as down; thus, in this case, associating acceleration with force is the means by which the student answers correctly.

2. Acceleration is (part of) force

We found that sometimes students use acceleration as an equivalent term to force: either acceleration *is* force or acceleration is part of a force exerted on the system. For example, in response to the Oval track question, a student wrote:

"Acceleration towards the interior of the track is the friction force that allows the car to turn on the track. Where the curve [is] sharpest/tightest [Point B and Point A] the net force/acceleration allows the car to turn. At Point C, the curve is not as strong, requiring less force towards the interior to stay on the track."

In this response, the student specifically refers to acceleration as though it *is* the force that allows the car to turn. Although the student incorrectly equates acceleration and force, they correctly identify the points on the oval trajectory where acceleration is largest/smallest, justifying their choice on the basis of the magnitude of the force. This is an example of how students might use the terms force and acceleration interchangeably in ways that at least do not hinder their learning, and may be productive or helpful.

C. Drawing on force ideas to determine trajectories

Students also frequently draw on forces to reason about trajectories of motion, often arguing that forces cause objects to take certain trajectories.

1. Gravity pulls objects down

Students often consider the impact of forces on the trajectories of objects, and more specifically, that gravity pulling objects results in certain trajectories. For example, responding to the Ball-on-ramp question, a student wrote:

"The main force acting on the ball at the instant the ball is pushed up is gravity. Gravity will pull down objects to the lowest point possible so the acceleration of gravity will point downwards (down the ramp) [...]."

This is an example where a student draws on the idea of force (gravity) to make sense of the ball's trajectory; specifically, gravity causes the ball to roll down to "the lowest point possible." Although the student did not arrive at the canonically correct answer (perhaps due to their not considering the normal force), in drawing on the impact of force, the student was able to consistently predict the resulting trajectory, which was helpful for the student's reasoning about acceleration. Although students most often drew on this resource in the context of the Ball-on-ramp question, connections between gravity and trajectory were also found to be productive in the context of the Comet question, in which students think the gravitational force by the sun is what pulls the comet towards the sun. Although the Comet question and the Oval track question share the feature of circular motion, gravity and trajectory is found to show up more often in the Comet question, likely as a result of the apparent mass at the center of the trajectory.

2. Force is needed to keep an object on curved trajectory

Students often drew on the idea that forces are needed to keep an object on its trajectory. This resource is particularly common in the Oval track question and the Comet question, where the trajectories are curved (e.g. oval and circular). For example, a response to the Oval track question stated:

"The magnitude of the acceleration also depends on the slope of the track since when it is 'flatter' there is not much force that needs to keep the car in circle while when the track is 'steeper' or more round there is a greater force required to keep the car in its trajectory."

In this response, the student draws on the connection between force and trajectory to reason about the change in the magnitude of forces throughout the oval trajectory; specifically, force is greater when the object takes a "steeper" curve and less so when the object takes a "flatter" curve. In using this resource, students were able to make inferences about the magnitude of the acceleration at different points along the trajectory.

C. Drawing on force ideas to reason about velocity

Similar to previous studies [8, 9], we found that students often connect force and speed.

1. Force causes objects to speed up/slow down

Students commonly drew on the idea that force has an impact on how an object's speed changes. Although we found students incorrectly relied on ideas such as a "larger force results in a larger speed," drawing on force was resourceful in certain ways for the students in our sample. For example, in response to the Comet question, a student wrote:

"Since the [comet] is moving away, the gravitational force causes it to slow down to 'turn around' until it reaches A and speeds up again."

In this response, the student makes sense of the comet's motion by drawing on the gravitational force between the sun and the comet. Specifically, when the comet moves toward the far end of its trajectory from the star, the impact of the gravitation force now is thought to make the star slow down. In this example, although the student did not specify the change in the magnitude of the gravitational force and its impact on the comet's motion, drawing on ideas of force informally is still productive for the students to correctly conceptualize the speed of the comet through the curviest part of its trajectory (slow down then speed up).

2. Going against (net) force slows down object

Students often drew on the resource that an object will slow down if its motion is opposite the direction of the net force. This idea is particularly common in the Ball-on-ramp question, which might be due to the force direction being constant (downward) in this case. For example, one student wrote:

"The higher up the ramp gets, the slower the ball will roll as there is gravity and possibly some friction acting upon it. As it goes down, the ball is no longer going against gravity, rather going with it which is why the ball is picking up speed as it goes down."

In this case, the student correctly identifies the forces exerted on the ball (gravity and friction), however miscounts for friction in the following step. Identifying a relevant force (gravity) supported the student in reasoning how the object changes its speed up and down the ramp.

V. CONCLUSION AND IMPLICATIONS

In kinematics instruction, instructors may have specific instructional goals for student learning, such as practice using graphical information and/or vector rules to find acceleration and velocity. In some cases, these learning goals prompt instructors to discourage students from using force reasoning in the context of kinematics, and to wait to introduce forces formally until after the kinematics unit. This study demonstrates that students in our sample frequently draw on force reasoning spontaneously in responses to kinematics questions, in many cases in ways that support them in correctly answering the question or forming generative connections between forces and kinematics concepts or forging relationships among kinematics concepts such as between acceleration and trajectory. Future studies might further investigate the impacts of contextual factors on students' use of force ideas and the affordances of force reasoning in kinematics contexts, i.e. whether students who use force reasoning more often answer kinematics questions correctly than students who do not, or whether there are particular contextual factors that shape the helpfulness (versus hindrance) of force reasoning in kinematics contexts. Future work might also explore whether using force reasoning in kinematics concepts changes the landscape of student attention—e.g., do students who use force reasoning focus less on kinematics representations and more on changes in motion.

In general, we interpret our findings as an existence proof that using force reasoning in kinematics does not necessarily disadvantage students from understanding kinematics. In fact, force ideas often served as resources for reasoning about kinematics for the students in our sample. Our findings suggest that kinematics instruction might benefit from building upon students' spontaneous ideas of force, rather than discouraging it.

ACKNOWLEDGMENTS

We are thankful to Lisa Goodhew, Rachel Scherr and the anonymous reviewers for feedback on the manuscript and to the instructors and researchers who helped with data collection. This material is based upon work supported by the National Science Foundation under Grant No. 1914572 and 1914603.

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