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Impetus-Like Reasoning as Continuous with Newtonian Physics

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Among the student ideas about forces discussed in the literature, perhaps the most commonly reported is the notion of an impetus force,[1-14] or the "belief that there is a force inside a moving object that keeps it going and causes it to have some speed."[13] For example, Clement[7] asked university students taking introductory mechanics to draw a free-body diagram for a coin that has been tossed upward. He found that students often drew an arrow in the direction of the coin's motion, at a point midway between the initial toss and the turnaround point, sometimes providing reasoning that suggested that the arrow corresponds to a "force from your hand" or the "force of the throw." Clement interpreted these responses as indicating that "student[s] may believe that continuing motion implies the presence of a continuing force in the same direction, as a necessary cause of the motion." As another example, in a study[4] conducted with undergraduate students at Johns Hopkins University, McCloskey, Caramazza, and Green asked students to draw the path a ball will follow after it exits the curved tubes pictured in Fig. 1. The authors found that students often drew curved trajectories for the ball exiting each tube, and they coined the term "curvilinear impetus principle" to describe students' reasoning. They write that students reasoned as though "an object constrained to move in a curved path acquires a curvilinear impetus that causes it to continue in a curved trajectory for some time after the constraints on its motion are removed."

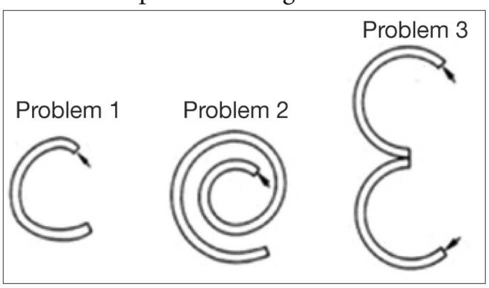

Fig. 1. Curved tubes from M. McCloskey and D. Kohl, "Naïve physics: The curvilinear impetus principle and its role in interactions with moving objects," *J. Exp. Psychol.* 9 (1), 146-156 (American Psychological Association). Reprinted with permission.

In the literature, the impetus force idea has been almost exclusively framed as a misconception or misunderstanding and as something to be addressed or altered by instruction. For example, McCloskey et al.[4] describe it as among "striking misconceptions" and "erroneous beliefs," and they say that their "data suggest that the students do not merely lack such knowledge [of fundamental principles of mechanics]; they espouse 'laws of motion' that are at variance with formal physics." Our paper offers an alternative interpretation of impetus-like responses: that they are the beginnings of sophisticated understandings of forces and motion—"seeds of science"[15] or "conceptual progenitors of expert understanding."[16,17] In other words, we propose that even though impetus-like responses are not fully Newtonian, they are still continuous with formal physics.

This is important because the judgments we make about students' ideas matter for what we do in instruction.[15,18] Misconceptions research in physics supports framing (i) impetus-like thinking as discontinuous with formal physics, and (ii) instruction in terms of correcting or replacing impetus-like reasoning.[8,19,20] Research that instead frames student thinking—including thinking that is canonically incorrect— as continuous with formal physics supports thinking about instruction as building from or refining impetus-like thinking.[21-24] Though neither framing of student thinking is "prescriptive with respect to method, and either could be invoked to support similar approaches ... the two perspectives differ," both in what instructors see in student thinking and in what practical next-steps are made obvious by interpretations of that thinking.[18]

Research context

In this paper we base our argument on our analysis of student responses to a question about the forces on a pendulum ball. This question was originally published in 1990 by Sadanand and Kess.[10] In that study, the *pendulum* question (Fig. 2) was included in a questionnaire whose purpose was to "attempt to identify [students'] misconceptions as precisely as possible." The authors say that their results "support the contention that many students invoke forces in the direction of motion even when there seems to be nothing that can generate that force," i.e., the impetus force idea.

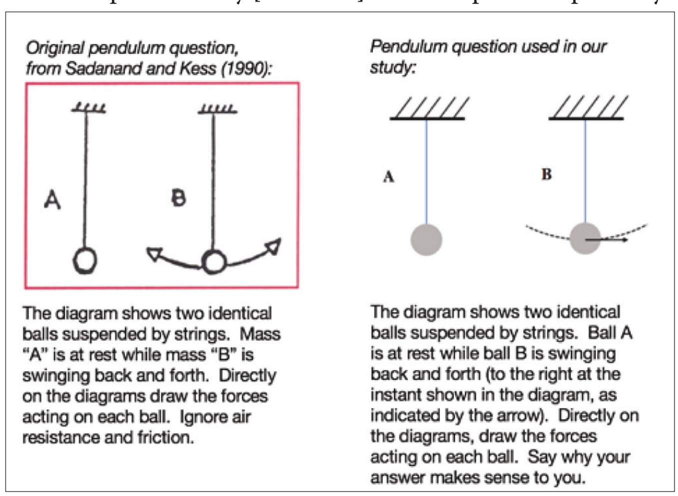

Fig. 2. Pendulum questions used (a) in the study conducted by Sadanand and Kess and (b) in our study. Leftmost figure reproduced from N. Sadanand and J. Kess, "Concepts in force and motion," *Phys. Teach.* 28, 530 (1990), with permission of the American Association of Physics Teachers.

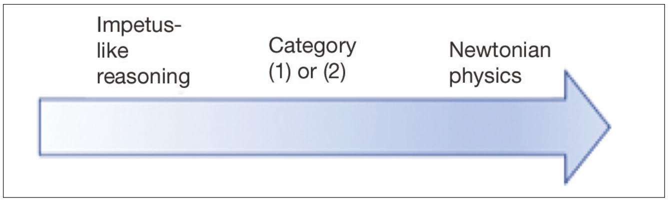

Fig. 3. Structure of argument for continuity of impetus-like reasoning with Newtonian physics. Location on continuum is not meant to scale; i.e., we do not mean to imply that reasoning in category (1) or (2) is "halfway between" impetus-like reasoning and Newtonian physics. Rather, we mean to suggest that impetus-like reasoning is continuous with reasoning in category (1) or (2), which is continuous with Newtonian physics.

In our study, we gave a slightly modified version[25] of the pendulum question (also in Fig. 2), hereafter the "*modified pendulum* question," to 577 students in introductory calculus-based physics courses at three different U.S. universities: Baylor University, Cornell University, and the University of Washington. Appendix A[26] approximates the racial/ethnic and wealth demographics of our study, which likely oversamples from Asian and wealthy populations and undersamples from Latinx and Black populations. We discuss these limitations in more detail in the appendix. All students received the questions on homework or exams after lecture instruction on Newton's laws.

We analyzed students' responses using a *resources* theoretical framing,[21-24] which emphasizes the sensibility and context-sensitivity of student thinking in physics and views learning as building on students' existing ideas. Resources theory poses student thinking as *continuous with* formal physics; in resources theory, even incorrect ideas can be "seeds" of robust physics understandings and practices. When we say that certain categories of student thinking are continuous with formal physics, we mean that we anticipate that these ways of thinking can develop toward canonical physics understandings, support engagement in rich disciplinary practices, help students to solve problems or create products that are personally meaningful to them,[27] and so on. Our project has focused on conceptual resources, and so we have mostly identified resources that we see as "seeds" of canonical physics concepts.

Our aim in this paper is to make plausible that impetus-like ideas can be thought of as continuous with Newtonian physics; this is a data-driven theoretical argument. We use student responses to the *modified pendulum* question to construct a hypothetical continuum between (a) responses we consider to be impetus-like and (b) Newtonian thinking. We do this using two additional categories of student thinking—(1) forces initiate motion and (2) moving objects keep moving—that act as a "bridge" between impetus-like thinking and Newtonian physics. That is, for each category, we argue that impetus-like thinking is continuous with student responses in that category, which are themselves continuous with Newtonian physics. The structure of our argument is illustrated in Fig. 3.

Examples of impetus-like responses from the modified pendulum question

A number of responses to the *modified pendulum* question reflect impetus-like reasoning.[28] For example, one student drew the free-body diagram for ball B in Fig. 4(a), which shows an upward arrow labeled F_T, a rightward arrow labeled F, and a downward arrow labeled mg. The student then explained that

> "…Ball B must have some force pushing it to the right at the point shown, in addition to tension and gravity, in order to be swinging."

We characterize this response as "impetus-like" based on Clement's definition of the impetus force as a "belief that there is a force inside a moving object that keeps it going and causes it to have some speed." In particular, this student argues that *in order to be swinging*, ball B must have a force pushing it to the right, implying that the force is what keeps the ball moving. Another student drew the free-body diagram for ball B in Fig. 4(b), which shows an upward arrow labeled F_T, a rightward arrow labeled F_m, and a downward arrow labeled F_g. This student wrote,

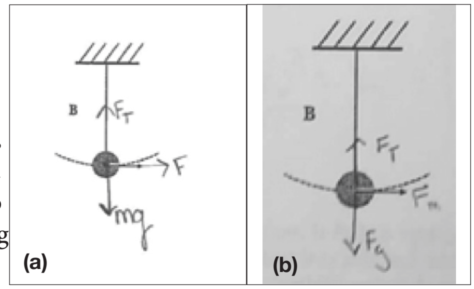

Fig. 4. (a) Free-body diagram for pendulum B. (b) free-body diagram for ball B associated with second impetus-like response.

> "…Ball B has 3 forces in the directions shown at the instance indicated of: force of tension, force of gravity, and force of movement. F_T and F_g cancel out at the instance, but F_m keeps it moving."

As with the first example, we interpret this response as impetus-like because it suggests that a force is needed to keep the ball moving.

Category (1): Forces initiate motion

Other responses to the *modified pendulum* question suggested that ball B is moving because a force was exerted on it at some time in the past—i.e., that a force caused the initial change in the motion of the ball from rest to moving, even if that force is not currently acting on it. Most of these responses included free-body diagrams with only tension and gravitational forces. For example:

> "…Mg & FT are still the only forces acting upon the [ball] at the instan[t] shown. The movement was caused by a force applied earlier but the force is not affecting the ball anymore."

> "…B has the same forces acting on it, the only difference is that it was given a force that has caused it to start swinging."

> "Ball B: There is no net vertical force, since its movement is mostly horizontal, so mg = F_T [sic]. I don't think there's a net horizontal force either. Sure, there is motion, likely caused by someone pulling the ball

> to the side and releasing it, but at the moment in question, no force other than gravity and tension are working on it."

This category of student responses helps us to construct a hypothetical continuum between impetus-like responses and Newtonian physics. That is, "forces initiate motion" responses share with impetus-like reasoning a view of forces as *agents that cause motion*, and they share with Newtonian physics the understanding that forces are not required to *sustain* motion. They are not equivalent to Newtonian physics. As with impetus-like responses, students seem to be looking for an individual, active agent as the original source of motion, rather than a net force in the direction of the pendulum ball's original motion that may have resulted from more "passive" forces[5] like gravity and tension.[30,31] That we can use this category of student responses to construct a continuum that connects impetus-like responses to Newtonian physics suggests to us that impetus-like responses are themselves continuous with formal physics.

Category (2): Moving objects keep moving

Still other responses to the *modified pendulum* question stated that ball B is moving because it was already moving, in some cases explicitly saying that this movement is not sustained by a force. Most students answering this way drew free-body diagrams for ball B that included only a tension and gravitational force. Examples of student reasoning in this category include:

> "In both cases, the only forces acting on the balls are the weight of the ball due to gravity, and the tension of the string. Ball B having an initial velocity does not change that."

> "This makes sense that they have the same forces acting on both because ball B is moving due to previous momentum, and not being pushed or pulled by a constantly applied force."

> "Both balls are at equilibrium at the bottom position of the pendulum. However, Ball B has an initial velocity so it continues to move…"

> "For A, the ball is at rest so the ball is at equilibrium. $|F^{\text{tension}}| = |F^{\text{gravity}}|$. Both forces are opposite and equal. For B, the forces are in equilibrium but the momentum and inertia of the ball allows the ball to continue moving."

Again, here we can construct a hypothetical continuum that connects impetus-like responses to "moving objects keep moving responses" and then to Newtonian physics. "Moving objects keep moving" responses share with impetus-like reasoning the notion that the motion of the ball is sustained by *something,* be it a force (in impetus-like reasoning) or a momentum or velocity (in "moving objects keep moving" reasoning). These responses share with Newtonian physics a recognition that forces are not needed to sustain motion and that motion does not "die away" in the absence of forces. However, these responses are not equivalent to Newtonian physics. In Newtonian physics, motion is a state that an object is in, influenced by external forces. In "moving objects keep moving" responses, students often responded as though motion is something objects *have*, or is sustained by something objects have. As with "forces initiate motion" responses, that we can use "moving objects keep moving" responses to construct a continuum connecting impetus-like responses to Newtonian physics suggests that impetus-like responses are themselves continuous with formal physics.

Discussion

The argument we have constructed in this paper offers an alternative to the framing of impetus-like thinking advanced in most physics education research literature. Rather than thinking of this idea as a misconception to address, our argument constructs impetus-like thinking as *continuous with* Newtonian physics—a beginning of sophisticated scientific understanding that instructors might build on.

We are currently in the process of developing and testing instructional materials that build on student resources for understanding forces. Given the early stage of that development, we are hesitant to offer concrete, prescriptive instructional interventions. What we feel we can recommend are general instructional implications that are rooted in resources-oriented research and instructional design. For example, one implication of our argument is that impetus-like thinking is an instructional *opportunity*, and the specific continua that we have constructed make visible some of the ways in which impetus-like thinking might develop toward Newtonian understandings. Resources-oriented theory and instructional design[22-24,32] poses a number of instructional moves that might facilitate this development, such as "schematiz[ing] instruction" to "promot[e] appropriate aspects of students' knowledge and reasoning."[18] For example, an instructor that hears reasoning similar to the second impetus-like student response above—"F_m keeps [the ball] moving"—might bring this idea into conversation with another student's answer that instantiates category-(1)-like thinking—that *forces initiate motion*. As we argue above, these ideas share a view of forces as *agents* that cause motion, but are also distinct from one another in important ways. The goal of a resources-oriented conversation that brings these ideas into contact need not be to *change* the impetus-like thinking into category-(1)-like thinking but to explore these similarities and differences, for the purpose of refining both kinds of ideas. Regardless of the specifics, our hope is that the argument we make here will contribute to a pausing in the reflexive evaluation of impetus-like thinking as needing to be addressed or fixed.

Acknowledgments

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25. We consider all of the changes we made to the original pendulum question to be clarifying, rather than changing its meaning. For example, we changed the image for Ball B to include a dotted line that traced the ball's trajectory and an arrow to indicate motion, rather than two curved arrows that indicate both the ball's trajectory and its motion.
26. Readers can view the appendix at *TPT Online,* http://dx.doi.org/10.1119/10.0003660, under the Supplemental tab.
27. B. W. Harrer, "Identifying Productive Resources in Secondary School Students' Discourse about Energy," PhD dissertation, Department of Physics, University of Maine (2013).
28. Resources theory[23, 29] would argue that aspects of the modified pendulum question likely cue some of these ideas and the ones reported later in the paper. For example, the arrow drawn on the pendulum ball may resemble (for some students) a free-body diagram and so cue ideas about forces.
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30. Students who asserted that the tension force equals the weight force may also seeking an active agent of motion. For example, the third quote above argues that $mg = F_T$ "since [the ball's] movement is mostly horizontal," suggesting that no vertical movement (or change in motion) implies no net vertical force.
31. The tendency to attribute current motion to past forces is also inconsistent with the Newtonian view that motion is relative. That is, observers in different inertial reference frames may disagree about the motion of other objects, but they will agree about past and current forces on those objects.
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