Newton's Zeroth Law: Learning from listening to our students

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Introductory physics students have difficulty with free-body diagrams. A principle we call "Newton's Zeroth Law" articulates important (but usually tacit) ideas underlying them. In this paper we explain our use of Newton's Zeroth Law in the introductory algebra-based course at the University of Maryland. We also discuss how one student's "misconception" led us to see that an alternative formulation of Newton's laws is possible, one that we had not previously considered, even after many years of teaching the subject.

Modern instructional advice encourages us to not just tell our students what we want them to know, but to listen to them carefully. This helps us to find out "where they are" in order to better understand what tasks to offer them that might help them learn the physics most effectively. Sometimes, listening to students and trying to understand their intuitions not only helps them, it helps us – giving us new insights into the physics we are teaching. We had such an experience in the Fall of 2003 in our algebra-based physics class at the University of Maryland.

A critical component in teaching Newtonian mechanics is helping students learn, in a situation with multiple interacting objects, to identify which of the many forces are relevant for determining a particular object's motion. One useful tool for doing this is the free-body diagram. Introductory physics students have difficulty with free-body diagrams. We often see them treat an initial push throwing a ball upward as if it lasted until the ball reached its highest point; we see them ignore the normal force exerted by an inanimate object; and we see them include both halves of a third-law pair as if they act on the same object. Some instructors and curriculum developers have found that these difficulties can be overcome with rigid labeling conventions or diagram algorithms. We wholeheartedly approve of such discipline.[1] Unfortunately, we have also observed that some students find the rules arbitrary and follow them because they're required, not because they see their value or relevance.

After years of helping students struggle with these problems, one of us (EFR) introduced a principle we call "Newton's Zeroth Law" that articulates the tacit idea underlying free-body diagrams. In this paper we explain our use of Newton's Zeroth Law in the introductory algebra-based course at the University of Maryland. We also discuss how one student's "misconception" led us to see that an alternative formulation of Newton's laws is possible, one that we had not previously considered, even after many years of teaching the subject.

The Class Environment

The introductory algebra-based course at the University of Maryland meets for three fifty-minute lectures each week in a lecture hall with stadium seating. Each lecture serves 100-200 students, most of whom are health and life science majors and most of whom are juniors and seniors. Almost all have successfully completed calculus (though most prefer not to use it) and 75% of them will have worked in a research laboratory by the end of their college careers. There is a required two-hour laboratory and a one-hour small group session that we run as a UW-style Tutorial.[2]

Since the Fall of 2000, the Physics Education Research Group at the University of Maryland has been reforming the algebra-based physics class as part of the "Learning How to Learn Science" project. Many students enter this class with a view of science knowledge as a collection of facts to be memorized (a view often confirmed for them by their other science classes) instead of as a way to make sense of experience and to develop a coherent and consistent framework of knowledge. Our reforms focus on helping students to understand the nature of scientific knowledge and learning rather than to accumulate a poorly understood collection of isolated facts. In order to achieve our goal, we have modified every part of the course – lectures, laboratories, homework and tutorials – in order to stress sense-making and coherence building. The details of these modifications will be described in another paper.[3]

For this paper, the important point of our modifications is that we focus on helping students build their physical intuition. Throughout the class, we ask the students to think about situations with which they might have personal experiences, to compare their intuitions with what the physics is telling them, to focus on what is right with their intuitions, and to see how those intuitions might be refined to match the physics they are learning.[4] In lecture, we have modified Interactive Lecture Demonstrations[5] to have students draw out, evaluate, and refine their intuitions. For our one-hour small-group sessions, we have modified University of Washington Tutorials to have students explicitly think about and evaluate their thinking. As a result, students get accustomed to thinking about and articulating their intuitions.

Introducing students to Newton's Zeroth Law

There are a number of hidden assumptions present in the Newtonian synthesis that seem so obvious to expert physicists that they often remain unstated in our instruction for novices. Unfortunately, they are not so obvious to the novice. One of these that we have found to be particularly difficult for students we state as *Newton's Zeroth Law*.[6]

At any instant of time, an object responds only to the forces it feels at that instant.

The crucial idea is that objects respond (and right now) to forces that they feel rather than to those they exert. We explain this to our students as "object egotism" -- that objects only care about themselves and "what you have done for them lately." Our comment, "many of you have had roommates like that" always brings a laugh and helps them remember the principle.

Another way we talk about Newton's Zeroth Law is to refer to *The Stanislavsky approach* or *method acting*. ("What's my motivation here?") The students are encouraged to "think inside the box" by imagining themselves to be a box being pushed across the floor. If you are *pushing* the box, what you notice is how hard you have to push. If you *are* the box, you not only feel the push but the drag of the ground on your bottom. Students are encouraged to think about being pushed across rough, sandpapery ground to make the image more vivid. Furthermore, in "becoming" the box, they have to realize that the box has no will or intent and only responds to what it feels.

A Tutorial on Newton's Zeroth Law

While hearing about Newton's Zeroth Law in lecture may help orient students to the idea, they can't be expected to apply it successfully without supported practice. In our course, this comes in the form of a tutorial that describes a person pushing on a pair of boxes one in front of the other. (See Fig. 1). The boxes are mounted on tiny rollers so that friction is negligible, and the person pushes with a force of 200 N. Box A has mass of 75 kg, and box B has mass of 25 kg. *How does the system move?* The tutorial begins by asking students to find the acceleration of the boxes. Many students readily

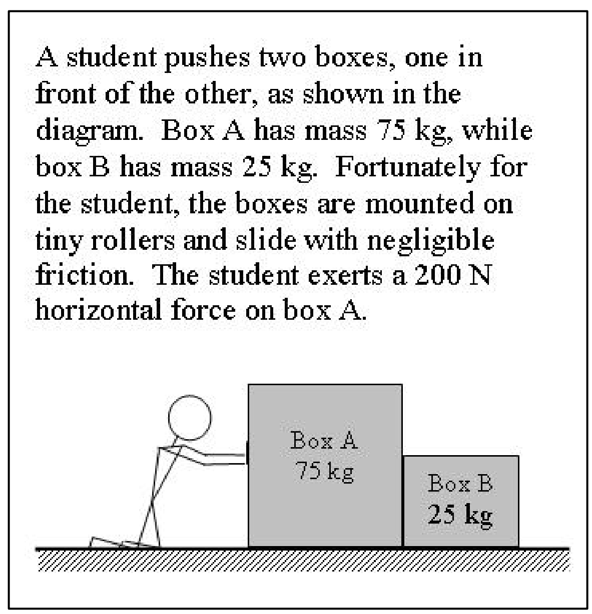
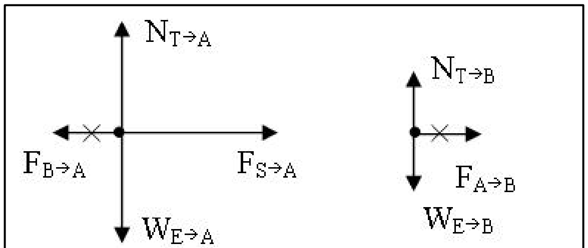


Figure 1. Excerpt from the tutorial on Newton's Zeroth Law.

agree that since the force that moves the pair of boxes is the 200 N force exerted by the person, the acceleration of the pair is[7] $a = F^{net}/m =$ (200 N)/(75 kg + 25 kg) = 2 m/s^2. A number of students, however, calculate two different accelerations for the boxes, assuming a net force of 200 N on each one. Students who make this error appear to think of the force by the person as acting on *each* box. Teaching assistants guide these students to recognize that since the blocks move together, they must have the same velocity and acceleration at all times, a conclusion that favors the first calculation.

Does the glassware break? The tutorial then informs the students that box B contains kitchen equipment, including glassware that is likely to break if the force on box B approaches 200 N. Students are asked to predict whether the glassware is likely to break in the current situation. Essentially all students – however they calculated the acceleration of the pair of boxes – predict that the glassware is at risk, usually explaining that the 200 N force that the person exerts is "transmitted" through box A to box B.

Free-body diagrams to the rescue! Next, students are asked to draw a free-body diagram for each of the boxes. Correct free-body diagrams are shown in Figure 2. For box A,



$N_{T\to A}$ = Normal force by table on box A
$W_{E\to A}$ = Gravitational force by earth on box A
$F_{B\to A}$ = Normal force by box B on box A
$F_{S\to A}$ = Normal force by student on box A
$N_{T\to B}$ = Normal force by table on box B
$F_{A\to B}$ = Normal force by box A on box B
$W_{E\to B}$ = Gravitational force by earth on box B

Figure 2. Free-body diagrams for Box A and Box B. The forces are not drawn to scale. The notation used is standard for the course; the forces marked with ´'s are a third-law pair. Although the horizontal forces are normal forces, we do not require that students recognize that detail.

some students initially draw just three forces (the weight force, the normal force, and the force exerted by the person). In this case, referring to Newton's Zeroth Law is directly helpful, and students often remind each other of it; by "being the box," students recognize immediately that box A feels box B pushing back on it, and add that force to their free-body diagrams. For box B, students usually draw the correct number and direction of forces. Many students label the force to the right as being 200 N and/or as being exerted by the person. Although these errors could also be corrected by application of Newton's Zeroth Law, teaching assistants don't correct them at this time; instead, they let students proceed with the tutorial, which helps them critically examine their initial assertions later on in the lesson.

The glassware doesn't break! The tutorial then asks students which forces are required to have equal magnitude by Newton's Third Law. Because of our prior special instruction, most students can do this correctly on their own. (The third-law pair is marked with ×'s in Figure 2.) Students are then asked to examine the implications of the prediction that the glassware breaks – that is, that the force on box B by box A ($F_{A\to B}$) is 200 N. The argument is as follows: If $F_{A\to B}$ were 200 N, then $F_{B\to A}$ would be also, according to Newton's Third Law. If $F_{B\to A}$ were 200 N, then the net force on box A would be zero, since the other horizontal force on box A is the 200 N force exerted by the person. If that were the case, then box A would not accelerate. Therefore, we must reject the possibility that $F_{A\to B}$ is 200 N. Once students have arrived at this conclusion, they calculate the magnitude of $F_{A\to B}$ based on the mass and (already-calculated) acceleration of box B. The magnitude of $F_{A\to B}$ is 50 N, well below the threshold for breaking the glassware.

Is the rule arbitrary? In the last part of the tutorial, students respond to a hypothetical student statement similar to ones that many of them actually will have made themselves by this point in the tutorial.

> "The rule says that you're supposed to label it $F_{A\to B}$. But this is one of those rules that's an arbitrary choice, like the rule that red means stop and green means go. Breaking this rule wouldn't actually

mislead you when you're solving a problem."

In discussing this, students decide for themselves on the importance of labeling forces in a manner consistent with Newton's Zeroth Law.

A student's alternative to Newton's Zeroth Law

While one of us (RES) was helping to teach the tutorial described above, a student we will call Melanie[8] had a concern that was initially difficult for us to understand. Her group was trying to calculate the magnitude of $F_{A\rightarrow B}$, and one of her partners explained (correctly) that since $F_{A\rightarrow B}$ was the net force on box B, they could find its magnitude by multiplying box B's mass by its acceleration. Melanie said, "Wait a minute. Wouldn't that be $F_{B\rightarrow A}$?"

When Rachel questioned her, Melanie said she understood what her partner was saying, and that it seemed reasonable. However, she thought it would make more sense if $m_B a_B$ were equal to $F_{B\rightarrow A}$, not $F_{A\rightarrow B}$. She said she understood that those forces had equal magnitude, so in some sense it didn't matter, but the mismatch bothered her. She tried to explain her concern to Rachel without much success. Rachel couldn't figure out what she was thinking. Melanie seemed to be saying that the motion of an object should be determined by the forces an object *exerts,* not the forces *exerted on it.* Why would a reasonable person think such a thing?

Then Melanie said, "You know, like a swimmer pushing off the wall." And suddenly, her point was clear. In fact, at that moment, it honestly seemed more reasonable than the alternative. Of course: if a swimmer wants to get going faster after making a turn at the end of the pool, she pushes harder on the wall. If you need to stand up, you do so by pushing down on the floor at your feet. To stand up faster you push harder. For a horse to succeed in pulling a heavy wagon forward, he needs to push hard, backward, on the ground at his feet. What could be more sensible than that?

We quickly realized that Melanie's way of thinking is a perfectly viable alternative to Newton's Zeroth Law. "Melanie's Zeroth Law" would read, "An object responds to the forces that it exerts at the moment that it exerts them." In Melaniean mechanics, each force on the free-body diagrams in Figure 2 would be replaced by its third-law complement. From such a diagram, one could determine the net force exerted *by* the object. The acceleration of the object would be opposite to the net force exerted by the object (as, of course, a swimmer accelerates in the direction opposite the push she exerts on the wall); that would be "Melanie's Second Law." Her third law would be identical to Newton's.

Rachel didn't say all that to Melanie, but she did paraphrase to Melanie what she thought she was hearing Melanie say, and Melanie confirmed her interpretation. Rachel was very impressed, and told Melanie so. Melanie's partners, who hadn't really been listening to what she was saying, perked up when they heard Rachel's praise and asked what was going on. Rachel said, "Melanie has an alternative to Newton's Zeroth Law!" and left. Melanie's partners turned eagerly to listen to her explain her idea.

Intuitions and Newton's Zeroth Law

Newtonian mechanics and Melaniean mechanics are mathematically equivalent. Using Newton's third law, Newton's second law can either be expressed in standard form

$$\vec{a}_A = \frac{1}{m_A}\sum_{B(\neq A)}\vec{F}_{B\rightarrow A} \qquad (1)$$

or in the equally valid alternative form

$$\vec{a}_A = -\frac{1}{m_A}\sum_{B(\neq A)}\vec{F}_{A\rightarrow B} \qquad (2)$$

The difference between Newtonian and Melaniean mechanics is more philosophical than technical.

However, the difference is still significant. Newton's and Melanie's second laws favor competing intuitions, particularly about "active" and "passive" objects. Consider these examples: When we think about a bowling ball being hit by a hammer, it seems unnatural to us (and to most of our students) to think that the bowling ball speeds up because it pushes back on the hammer. It's more natural to think of the bowling ball as responding to the hammer – in line with the traditional form of Newton's second law. On the other hand, when we think about a swimmer turning at the end of the pool by pushing off on the wall, it seems perfectly natural to most of our students (and even to us) that the swimmer is accelerating because she is pushing on the wall and not because the wall is pushing her. In this case, Melanie's second law is more intuitive.

The difference is which of the pair of Newton's-third-law forces we focus on. When we think about an inert object, it seems more natural to think about forces acting on the object. When we think about an active agent, it seems more natural to think about the agent exerting forces on its environment in order to move. Indeed, for active agents we could use a "mixed" method: when forces impinge on the agent from the outside, they would appear in Newton's second law as usual, but when the agent actively exerts forces, the exerted forces would appear in Newton's second law with a minus sign (and the more commonly used third law pair forces acting on the agent would be omitted).

As physicists, we tend to focus on the behavior of inanimate objects, so the conventional form (Eq. (1)) is more natural for us. For our students – indeed, for anyone thinking about their personal experience with forces (and perhaps especially for biologists) – the alternative form (Eq. (2)) appears to make more intuitive sense.

We don't advocate teaching Newton's laws in Melanie's form. Students are easily confused about which forces belong in Newton's second law for a particular object and giving them alternatives when their understanding is shaky is probably not a good idea. However, if we understand (and respect) our students' intuitions as legitimate alternative ways of thinking about the physics they are learning, we can be more supportive of our students' difficulties in learning conventional physics.

Conclusion

Melanie's question reminds us that Newton's Zeroth Law, which is generally treated as self-evident (if tacit), is not in fact the unique way to describe motion in the Newtonian world. It is, rather, a conventional and philosophical choice made by physicists. It is part of the way that we choose to think about the world, not part of the world itself.

We draw two conclusions: First, it's no wonder that students see alternatives to the Newtonian mechanics that we are familiar with. There *are* alternatives and our students' intuitions should be given respectful consideration. Second, we should retain enough humility to appreciate that, even though we may have taught a subject for many years, listening carefully to our students' intuitions can help us develop new insights into the physics we know well.

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[1] In our classes, we use the notation $F_{B \rightarrow A}$ to indicate the force object B exerts on object A.

[2] L. C. McDermott, P. S. Shaffer, and the Physics Education Group at the University of Washington, *Tutorials in Introductory Physics* (Prentice Hall, 1998).

[3] A discussion of this project and some of its results can be found in E. F. Redish, "A Theoretical Framework for Physics Education Research: Modeling student thinking," in E. F. Redish, C. Tarsitani, and M. Vicentini, eds., *Proceedings of the Varenna Summer School, "Enrico Fermi," Course CLVI*, section 6.1.

[4] A. Elby, "Helping physics students learn how to learn," *Phys. Ed. Res. Suppl. to the Am. J. Phys.* **69** S54-S64 (2001).

[5] D. R. Sokoloff and R. K. Thornton, *Interactive Lecture Demonstrations* (John Wiley & Sons, 2001).

[6] One of us (EFR) was inspired to identify "Newton's Zeroth Law" by David Hestenes' careful discussion in *A New Foundation for Classical Mechanics* (Kluwer, 1986) chapter 9. There, Hestenes identifies a more general tacit principle as "the Zeroth Law."

[7] We try to always express Newton's second law in this form rather than as the more conventional "$F = ma$" since students in this class frequently interpret a functional relationship as "a way to calculate the thing on the left," which tends to make them read the conventional form as "acceleration causes force." We want to encourage them to think about it the other way round.

[8] This is a gender-correct pseudonym