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Examining Student Reasoning in Introductory Physics: Reversing the Chain

William S. Johnson
University of Maine

EXAMINING STUDENT REASONING IN INTRODUCTORY PHYSICS:

REVERSING THE CHAIN

by

William S. Johnson

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Advisory Committee:
MacKenzie Stetzer, Assistant Professor of Physics
Kathleen Ellis, Lecturer in English
Saima Farooq, Lecturer in Physics
John Thompson, Professor of Physics
Michael Wittmann, Professor of Physics

ABSTRACT

While physics education researchers have investigated student conceptual understanding of specific topics in physics for over thirty years, much less is known about the ability of students to construct qualitative inferential reasoning chains. Such reasoning chains are ubiquitous in scaffolded, research-based instructional materials. As part of a multi-institutional effort to develop instruments to probe student reasoning skills, this thesis describes an investigation into whether the direction of a question can influence the ability of the students to construct correct reasoning chains. Reasoning reversal tasks were administered to introductory calculus-based physics students at the University of Maine. Students were randomly presented with one of two versions, where one version involves students determining how a variable changed to create the observed outcome, and the other version presents the students with the changed variable and asks for the outcome due to the change. In this study, student data from four different semesters were collected and analyzed, including data from modified versions of the original reasoning reversal tasks. The results from this study suggest that in certain contexts, students could be more successful in constructing correct reasoning chains in one direction than in the other. In other contexts, these results were not found to be true where the difference in reasoning chains was primarily due to the constraints associated with the question's answer options.

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INTRODUCTION

As part of a larger investigation of student reasoning chains at the University of Maine, this study explores how question design in physics may influence the ability of students to use proper reasoning. The goal of this investigation was to determine the extent to which student ability to construct a correct reasoning chain depends on the "direction" of the reasoning, as established by the question posed to the students. We therefore presented reasoning reversal tasks in which forward and reverse versions of a physics question requiring a particular line of reasoning were randomly administered to students in order to examine the impact of reasoning direction on student performance.

For many years, physics education research (PER) has focused on student conceptual understanding of specific topics in introductory physics [1]. For example, McDermott and Shaffer investigated student understanding of simple dc electric circuits, primarily using written questions [2,3]. These questions were designed to reveal where students struggled, which allowed the researchers to determine what needed to be addressed in the instructional materials. McDermott and Shaffer identified broad areas of difficulties involving general, circuit, potential difference, and resistance problems with subcategories for each. General difficulties focused on a lack of familiarity with circuits, while circuit problems highlighted how students believed current behaved. Also mentioned were potential difference difficulties, which addressed the nature of batteries (and their connections in circuits), and resistance difficulties, which emphasized how resistor configurations were often overlooked. Other studies by McDermott and Shaffer focused on the application of Newton's laws, another area in which students were observed to struggle [4]. Many of these efforts led to the development of research-based instructional materials designed to address the identified difficulties and to develop a coherent conceptual framework for introductory physics [5].

McDermott later discussed the nature of PER, highlighting the difference between traditional education research, which focuses on theories and methodologies, and PER, which investigates student understanding [6]. While research-based instructional materials have been shown to be very effective at improving conceptual understanding, it is well known that student performance on tasks targeting the same concept can vary dramatically from task to task. As a specific example, research conducted using paired screening and target questions requiring the same conceptual understanding revealed that students who demonstrated the requisite understanding on the screening task were often unable to answer the target question correctly, abandoning the correct formal reasoning in favor of a more intuitive response [7, 8].

The use of intuitive-based reasoning rather than analytical or formal approaches in such cases has been interpreted through the lens of dual-process theories of reasoning, which suggest that two processes are involved in reasoning decision-making: the fast and automatic *heuristic process* and the slow, thought out, and rule-based *analytic process* [9,10]. Kryjevskaia, Stetzer, and Grosz applied Evans' heuristic-analytic theory to student performance on paired questions, on which students appeared to respond to the target question on the basis of their intuitive models without engaging the analytic process to check their initial ideas [7]. This led to reasoning approaches primarily motivated through previous experiences outside the classroom rather than the more formal, rule-based approaches covered during instruction. By apparently ignoring or shortcutting the analytic process, researchers questioned whether students had the metacognitive skills necessary to understand how their reasoning was flawed [8]. Such findings suggest that the poor performance on certain tasks, even after research-based instruction, may have more to do with the nature of student reasoning and less to do with student conceptual understanding [11].

Currently, research on student reasoning is continuing at the University of Maine, focusing on how question design influences the reasoning chains used by students. One study explores how students respond when they are given correct parts of a reasoning chain and are asked to organize them to create a complete chain before selecting an answer [12]. The dual-process theories mentioned previously were prevalent due to one question having an intuitive incorrect response while the other forced students to use an analytical process to solve. Another study involved the use of hypothetical student reasoning chains, prompting students to predict what the hypothetical student would answer [13]. It was suggested that students tend to be able to arrive at the correct conclusion for a given reasoning chain successfully, but further analysis is necessary.

This suggests that a better understanding of student reasoning skills, particularly the ability to construct qualitative inferential reasoning chains, is needed. Given the apparent sensitivity of student reasoning to contextual cues and salient distracting features (as a result of the role of the heuristic process), it is plausible that student ability to construct a given reasoning chain may be enhanced or suppressed by the direction in which they are asked to construct it (*e.g.*, to start from a change in the outcome of an experiment and infer the modification leading to this change, or to start from an experimental modification and to determine how that will change the outcome of the experiment).

METHODS

To understand the reasoning behind student responses to a challenging question, tasks that highlight difficulties must be developed. Specifically, we have focused on the reasoning chains utilized by students when a question is presented in multiple formats. This involved creating a situation where the same information can be presented in different ways to elicit complex reasoning chains that address the same problem from opposite directions. Students are randomly presented with one of two versions, where one version involves students determining how a variable changed to create the observed outcome, and the other version presents the students with the changed variable and asks for the outcome due to the change.

The target group for the questions was introductory calculus-based physics students after the required materials had been covered in their recitations. The reasoning questions administered spanned both PHY 121 and PHY 122 due to the concepts being utilized. A question involving Newton's second law was presented in PHY 121, while Kirchhoff's circuit laws were highlighted in the question administered in PHY 122. Two data collection methods were used over a two-year period. During the first year, the questions were presented in an online exam review, while the second year saw the questions being administered during recitation. Both data collection methods were for participation credit, and the data were anonymized before analysis occurred.

Data analysis was conducted using modified grounded theory, in which categories were primarily constructed based on the reasoning provided in the student responses. The analysis was conducted with the help of Dr. MacKenzie Stetzer, who challenged categories that didn't seem to make sense based on either his own analysis or the larger PER literature. When such challenges occurred, both sets of categories were examined in depth to determine which better characterized the reasoning chains presented by students.

RESULTS: FORWARD – REVERSE REASONING TASK

In a Forward/Reverse (FR) task, students are presented with one of two versions of a question. The difference between the two versions is found in what information is given and what information the student is expected to solve for. The forward version will contain a certain piece of information in the prompt that is directly translated to the reverse version as the answer.

Forward – Reverse Original Incarnation

Newton's Laws: Three Blocks Forward

Students were presented with a three-block system being pushed by a constant force (Figure 1). Students were told that the mass of the center block was increased while the pushing force was kept constant. The students were then asked whether the net force on block A increased, decreased, or remained the same.

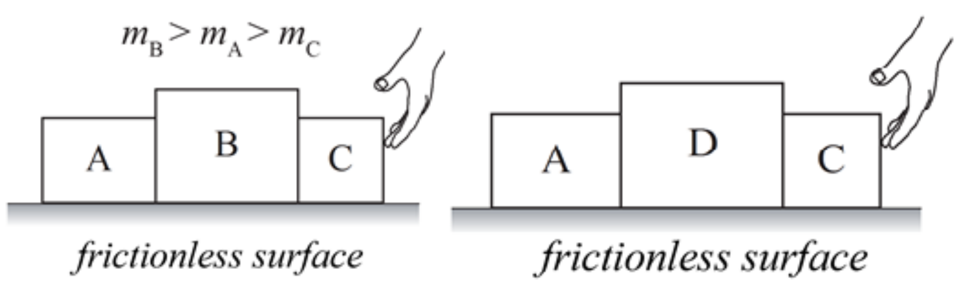

Figure 1: Three block system before and after more massive block D added.

In order to arrive at a correct response, students needed to recognize that the acceleration of the system decreased due to a constant pushing force (due to the hand) and an increased mass. From this they connect the system's acceleration to the acceleration of block A and conclude that, due to a decreased acceleration and a constant mass (for block A), the net force must have decreased using Newton's second law.

Newton's Laws: Three Blocks Reverse

Students were presented with a three-block system being pushed by a constant force (Figure 1). Students were told that the net force on block A decreased while the pushing force remained constant. Students were asked whether the mass of block D was greater than or less than the mass of block B.

The net force on block A has decreased, but the mass is the same, this means that the acceleration must have decreased due to Newton's second law. For the acceleration of the system to decrease with the same constant force, the total mass of the system must have increased, which means the mass of block D is greater than block B.

Newton's Laws: Three Blocks Results

The three blocks scenario presented is noticeably difficult, which the results would reinforce. Students struggled with both versions of the question, where the forward task yielded a lower success rate (17%) compared to the reverse task (37%) (two-tailed p-value of .006).

Forward (Net force on A) (N=81)			Reverse (Mass of D vs. B) (N=82)		
Increased	Same	**Decreased**	**Greater**	Same	Less
38%	45%	**17%**	**37%**	1%	62%

Table 1: Results from the three blocks reasoning reversal task with correct answers in bold. The correct forward answer was the net force on block A decreased. The correct reverse answer was the mass of block D was greater than the mass of block B.

Upon closer inspection of the data, distinct reasoning chains appear, allowing us the ability to better understand how pervasive a particular line of reasoning is throughout the class.

	Forward (N=81)	Reverse (N=82)
Correct Reasoning	4%	13%
Incomplete Correct Reasoning	7%	10%
Δ Mass $\rightarrow$ Δ Force (implicit assumption of unchanged acceleration)	30%	52%
Same Pushing Force	15%	0%
System Unchanged by New Mass	9%	0%
More Mass and Smaller Acceleration $\rightarrow$ Same Force	6%	0%
Other/Unclear	15%	14%
No Explanation	14%	11%

Table 2: Categorization of results showing different chains of reasoning for the two versions of the three blocks task.

i. Correct Reasoning

Two approaches were considered correct: Newton's second law and allocation of forces. The Newton's second law approach was only used by two students who noted the decreased acceleration of the system before addressing its effect on block A; one student noted, "…the mass of block A remains the same, so if the acceleration of block A decreases, then the force exerted on block A must also decrease." Allocation of forces involved the student recognizing the need for more force to move a more massive object, which would leave less of the total constant pushing force available for block A; for example, one student wrote, "Because more force is contributing to the movement of block D, there is less force being applied to block A." While this force allocation is a consequence of a correct application of Newton's second law to the system as a whole, these lines of reasoning, as presented, aren't entirely complete. Even so, such reasoning was categorized as correct.

ii. Incomplete Correct Reasoning

While fundamentally correct, students would neglect to include information in their reasoning, leading us to assume they understood the significance of that missing piece. A clear example involves allocation of force for the forward version: "It takes more force to move Block D." This is a true statement, but we don't know why the student concludes this or the justification for the claim, which makes it incomplete.

iii. Change in Mass Implies Change in Force (Implicit Assumption of Unchanged Acceleration

The most popular response for both versions highlighted a problem with multivariable equations containing multiple unknowns [14]. This response comes from assuming acceleration is constant when using Newton's second law, which makes force directly proportional to mass. Not all students referenced the need for the acceleration to be constant, but some did so explicitly; for example, one student wrote, "Because F=ma, and m was increased while a was unchanged, the net force will increase." Some simply stated Newton's second law with only some reasoning which led us to assume they thought the acceleration was constant.

iv. Same Pushing Force

While only seen in the forward version for the force remains the same option, students argued that the net force didn't change since the only horizontal force was the pushing force, which was constant. For some, this was due to the frictionless surface, but most simply said something to the effect of the following: "The force of the hand on the blocks does not change, therefore, the force being exerted on block A does not change either."

v. System Unchanged by New Mass

Again, this response was only seen in the forward version and was conceptually similar to the Same Pushing Force response, except students explicitly stated that more mass wouldn't affect the net force on block A. Arguments due to the frictionless surface were fairly common, with one student noting, “Because this is a frictionless table, the fact that block D is heavier than block B does not have an effect on the net force it exerts on block A.”

vi. More Mass and Less Acceleration Cancel

Revolving around problems with multivariable equations, students failed to recognize that the increase in mass and the decrease in acceleration don’t cancel. This error led to responses like, “Force = ma. Since force remains the same, acceleration will change with the mass change. [T]he force exerted on block A will then be the higher mass times the lower acceleration.” This reasoning could also be seen as confusion between the net force on the system and the net force on block A. While similar to the same pushing force category, students addressed the existence of changes to the system (acceleration and mass), which led to a distinct category.

vii. Other or No Reasoning

There were a large number of responses that didn’t fit into broad categories as well as many answers without accompanying responses. The other category was comprised of reasoning that either was entirely unique or didn’t contain enough information to place comfortably in a category. For example, a response of “f=ma” was placed in this category.

Correct answers were typically found in the correct reasoning and incomplete correct reasoning with some in the other or no reasoning category. For the forward version (exclusively), the remains the same reasoning was broken into three categories: same pushing force, system unchanged by new mass, and more mass and less acceleration cancel. The less mass answer (reverse) and the greater net force answer (forward) were categorized almost entirely in the direct correlation between mass and force category (*i.e.*, acceleration is unchanged) of reasoning.

For the reverse version, remains the same wasn't an answer option, which suggested that the constant pushing force on the three-block system couldn't lead to the mass of block D being the same as block B. This couldn't be said for the forward version, however, where the remains the same option was appealing to those who noted the constant pushing force. With 45% of the students on the forward version choosing the net force remains the same on block A, the similarities and differences in reasoning chain prevalence between the two versions were difficult to determine.

Kirchhoff's Circuit Laws: Bulb Brightness Forward

Students were presented with an electrical circuit consisting of a battery and bulbs (Figure 2). Students were told that the switch was originally closed and is now opened. Note the switch was simply represented by a box so as not to provide any unintended cues on the reverse version (discussed below). Students were asked to determine whether the brightness of bulb D would increase, decrease, or remain the same after the change.

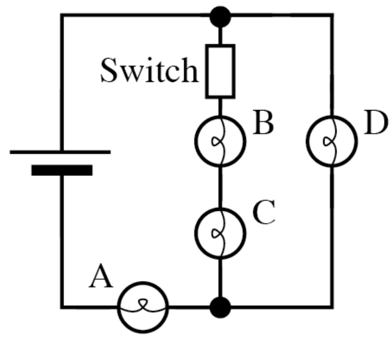

Figure 2: Circuit configuration containing ideal battery, switch, and bulbs.

When the switch is opened, the resistance of the circuit increases due to the removal of a parallel branch. This increase in resistance leads to a decrease in the current through the battery using Ohm's law. Bulb A now has less current through it than before, and thus less voltage across it, which means that bulb D must have more voltage across it than before to conform with Kirchhoff's voltage law. This increase in voltage corresponds to the brightness of bulb D increasing.

Kirchhoff's Circuit Laws: Bulb Brightness Reverse

Students were presented with an electric circuit consisting of a battery and bulbs (Figure 2). Students were told that the brightness of bulb D increased due to the position of the switch changing. Students were asked whether the change involved opening or closing the switch.

If the brightness of bulb D has increased, then the voltage across it must have increased. To achieve this, the voltage across bulb A must have decreased in accordance with Kirchhoff's voltage law, which means the current through the battery must have decreased as well. The resistance in the circuit must have increased to achieve a decreased current and, due to the properties of parallel branches, the switch must have been opened since this would disconnect the parallel branch from the circuit.

Kirchhoff's Circuit Laws: Bulb Brightness Results

Significantly more students gave correct answers for the reverse version than the forward version (two-tailed p-value of .006). Correct responses for reverse (62%) were almost double that for forward (35%), suggesting there may be a more straightforward approach to the problem in one direction than the other.

Forward (Brightness of D) (N=54)			Reverse (Change in switch) (N=55)	
Increased	Same	Decreased	**Opened**	Closed
35%	39%	26%	**62%**	38%

Table 3: Results from the circuits reasoning reversal task with correct answers in bold. Correct forward answer was the brightness of bulb D increased. Correct reverse answer was the switch was opened.

Based on the previous data, we would expect to see a difference in correct reasoning between the two versions, since one group answered correctly more than the other. However, we found that students for both versions were unable to construct correct reasoning chains regardless of how they answered.

	Forward (N=54)	Reverse (N=55)
Correct Reasoning	2%	2%
Incomplete Correct Reasoning	4%	5%
All Current to D (implicit assumption of constant current through battery)	28%	42%
Ohm's Law (current through battery and current through bulb D confusion)	9%	22%
Independent Branches	33%	0%
Switch Confusion	9%	5%
Other/Unclear	8%	20%
No Reasoning	7%	4%

Table 4: Categorization of results showing different chains of reasoning for the two versions of the circuits task.

i. Correct Reasoning

On each version of the question, only one student was able to arrive at the correct answer using correct reasoning. The student answering the forward version assigned each bulb the same arbitrary resistance of one and solved for all of the relative quantities (such as current, voltage, and total resistance) when the switch was open and when the switch was closed, leading to the conclusion that "… Opening the switch increases the potential difference across D, which increases its brightness."

ii. Incomplete Correct Reasoning

While being technically correct, these students didn't provide enough reasoning for their answers to be satisfactory, which led to correct conclusions without the necessary starting point. This was typically manifested in correct assertions without any reasoning to back them up; for example, one student wrote, "Objects in [parallel] have the same voltage, so BC and D all have the same voltage. If the switch is closed, that increases the voltage to D and causes it to increase in brightness."

iii. <u>All Current to D (implicit assumption of constant current through battery)</u>

By far the most common style of reasoning (when including both versions), students simply stated that by removing the branch containing bulbs B and C, the current was diverted to the branch containing bulb D. While not being entirely incorrect due to the current only having one path, the reasoning is flawed since it is grounded in the implicit assumption that the battery current doesn't change: "All of the current in the circuit would then flow towards D, instead of breaking off at the junction."

iv. <u>Ohm's Law (current through battery and current through bulb D confusion)</u>

While Ohm's law is not incorrect to use by any means, the misuse of it is. Students consistently inferred that the current through the battery was the same as the current through bulb D: "The increased resistance and constant voltage would cause us to conclude that when the switch is closed the current increases causing the light to be brighter." Other issues involved how the resistance of the circuit is changed when the switch is opened or closed.

v. <u>Independent Branches</u>

The line of reasoning involving independent branches was only observed in the forward version due to the nature of the logic and the answer choices. In order to conclude that the switch doesn't affect the bulb D branch, there has to be an option where the bulb's brightness doesn't change, which isn't available for the reverse case. When the option was available, students believed that by being in parallel, the removal of a branch wouldn't affect the other branch. For example, one student wrote, "… But they [bulbs A and D] were already in series before so bulb D should remain the same [when] the parallel [branch] is taken out."

vi. <u>Switch Confusion</u>

An unexpected problem arose for both versions of the question where students were unclear as to what the switch represented. Based on their reasoning, some students treated the switch as though it was a dam where opening it led to the current being allowed to travel to bulbs B and C, which is the opposite of how the switch behaved. For example, one student answering the reverse version reasoned, "With the switch open B+C and D are now in parallel so the resistance the current experiences is less since there are two routes for the current to go through."

vii. <u>Other or No Reasoning</u>

There were cases where students used reasoning that simply didn't fit in with the larger categories and rather than add a new grouping for one student, they were added to other. In other cases, students provided either no reasoning or meaningless responses such as "Magic."

Correct answers were typically found in the correct reasoning and incomplete correct reasoning with some in the other or no reasoning category. For the forward version (exclusively), the remains the same answer was only seen in the independent branches category. The switch was opened answer (reverse) and the increased brightness answer (forward) were categorized into Ohm's law difficulties and switch confusion.

Students for both versions of the task were generally unable to construct correct or partially correct reasoning chains to arrive at their answers, with 6% for forward and 7% for reverse. Ignoring their ability to reason correctly, we wanted to focus on what types of reasoning were used for each version of the task and whether the numbers were comparable. Unfortunately, similar to the three-block task, the remains the same option for the forward version was appealing enough that the number of students using independent branches reasoning was large enough such that the other categories couldn't comfortably be compared between the two versions. Again, this was due to the implicitly given information in the reverse version that something had to change in order to arrive at the result. This precluded the use of reasoning chains that the students answering the forward version found appropriate and appealing.

Forward – Reverse Modifications

After running the original reasoning reversal tasks, it became clear that modifications were needed in order to extract more useful information from student responses. One suggestion focused on the constrained nature of student responses, where the forward version allowed for more lines of reasoning due to the presence of more answer options than the reverse version. For example, the three blocks question allowed students to focus on the constant pushing force as a reason for there being no change whereas the reverse version didn't allow for that line of reasoning since the answer choices made it clear that a variable changed. This made it difficult to compare the prevalence of reasoning chains in both directions due to the large number of students who used remains the same reasoning for the forward version. The number of answer choices was also concerning if students were randomly choosing an answer where there were more options in one direction than the other. We were unsure if this was a factor, but due to the constrained reasoning options, we felt that creating a second forward version without the remains the same option would be beneficial for making meaningful comparisons after data analysis. This way, if the reasoning and performance on the two forward versions differ from that on the reverse version, the differences can be attributed primarily to the direction of the question/reasoning and not to the constraining of reasoning paths due to the constrained answer options.

In addition, specifically for the circuits task, we found that a source of confusion for students was in how the switch was presented in Figure 2. Students were unsure what the switch would look like when it was open and when it was closed due to our need for the drawn switch orientation to not influence student perception of the circuit. For example, if the switch was presented as open in the diagram and the question wanted to know the orientation of the switch after a change, students might pick open due to it being shown that way. This type of problem had already been observed in the three blocks task, where one trial saw the more massive block D looking larger in the diagram despite the fact that students needed to conclude this for themselves on the reverse version. This led to responses built solely around the size of the diagram rather than the given information. To address this for the circuits question, we added a second diagram describing what the switch would look like if it were open and if it were closed. To make the diagram as clear as possible, the added switch diagram was constructed to look like the diagrams seen in the course materials.

The last change involved the medium through which the students had the questions administered. We felt that some of the hard-to-categorize online responses may have been an artifact of online administration, and that pencil-and-paper written questions might be easier to interpret due to the ability to draw and annotate diagrams. This change shouldn't affect the ability of the students to answer the question since the students who typed can do work by hand before submitting, but it makes it easier for data analysis and categorization if students are having difficulties regarding describing their work.

Forward – Reverse Updated Incarnation

Newton's Laws: Three Blocks

The question remained the same as the original for both the forward and reverse versions, except, in this instance, a third version was given where the prompt was the same as the forward version with only two answer options: the net force on A increased or the net force on A decreased.

Newton's Laws: Three Blocks Results

Students performed better on the reverse task (59%) than the forward task (39%) (two tailed p-value of .006) and the students answering the constrained forward version performed similarly to the forward task (47%). It is important to note, however, that there is a force remains the same category in Table 4 for the updated forward version despite the answer option not being given in the question; this stems from the fact that some students indicated that the force remained the same despite the fact that it wasn't a possible answer choice, thereby disregarding the given instructions (11%).

Forward (Net force on A) (N=94)			Forward 2 (Net force on A) (N=94)			Reverse (Mass of D vs. B) (N=96)	
Increased	Same	**Decreased**	Increased	Same *	**Decreased**	**Greater**	Less
16%	45%	**39%**	43%	11%	**47%**	**59%**	41%

Table 5: Results from the updated three blocks reasoning reversal task with correct answers in bold. For forward 2, the remains the same option (indicated by *) was not given, but students selected it despite this. Correct forward and forward 2 answer was the net force on A decreased. Correct reverse answer was the mass of block D was greater than the mass of block B.

While both forward versions had a similar percentage of correct answers to correct reasoning, the reverse version had a large number of students who used correct reasoning when answering correctly. The number of incomplete reasoning chains was almost zero (one student) for the reverse task suggesting that students who answered correctly were either going to be entirely correct or they were going to use incorrect reasoning.

	Forward (N=94)	Forward 2 (N=94)	Reverse (N=96)
Correct Reasoning	21%	28%	48%
Incomplete Correct Reasoning	11%	10%	1%
Δ Mass → Δ Force (implicit assumption of unchanged acceleration)	20%	37%	41%
Same Pushing Force	22%	5%	0%
System Unchanged by New Mass	13%	3%	0%
More Mass and Smaller Acceleration → Same Force	3%	2%	0%
Other/Unclear	10%	15%	10%
No Explanation	0%	0%	0%

Table 6: Results highlighting different chains of reasoning for updated three-blocks task.

Looking first at the two forward versions, we saw an increase from unconstrained to constrained in correct or partially correct reasoning and an increase in the number of students who reasoned that the change of mass is directly correlated to the change in force. This implies that constraining the forward version affected what reasoning chains were used by the students. The increase in the mass/force reasoning was likely due to the nature of the remains the same reasoning and the mass/force reasoning where a variable (in this case acceleration) is constant/unchanged in both, suggesting that students are drawn to reasoning chains that leave variables constant in multivariable expressions like Newton's second law.

Comparing the constrained forward to the reverse saw a difference in correct or partially correct reasoning, with the reverse version statistically higher (two tailed p-value of .077). This increase in correct reasoning suggests that the direction of the question affects the ability of the students to construct correct reasoning chains and isn't affected by answer constraints. However, the prevalence of mass/force reasoning was almost identical suggesting that the direction of the question doesn't affect certain lines of reasoning which are more affected by question constraints.

Kirchhoff's Circuit Laws: Bulb Brightness

Similar to the updated three-blocks scenario, the original question for the forward and reverse versions remained the same, except for a new circuit diagram (Figure 3) and an added version where the answer options were limited to: brightness of bulb D increased or brightness of bulb D decreased.

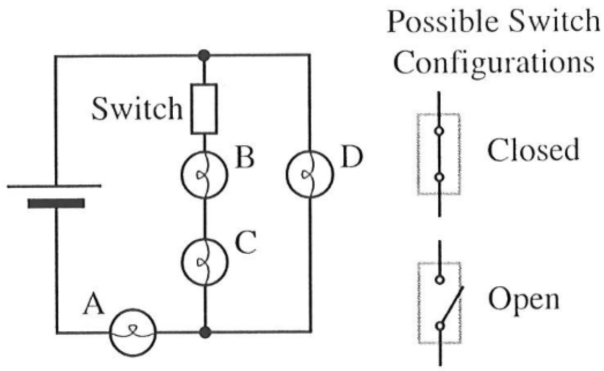

Figure 3: Same circuit as Figure 2 with added switch orientations.

Kirchhoff's Circuit Laws: Bulb Brightness Results

Students performed similarly on the updated forward task (86%) and the reverse task (79%), while the forward task lagged behind both (65%). The constrained forward task had statistically higher correct answers than the forward task (two-tailed p-value of .006), while the reverse version was marginally statistically higher than the forward version (two-tailed p-value of .08). Interestingly, the percentage of students answering with a decreased bulb D brightness on the updated forward task (14%) was essentially the same as the percentage for the forward version (17%) despite there being one less option.

Forward (Brightness of D) (N=63)			Forward 2 (Brightness of D) (N=64)		Reverse (Change in switch) (N=66)	
Increased	Same	Decreased	**Increased**	Decreased	**Opened**	Closed
65%	17%	17%	**86%**	14%	**79%**	21%

Table 7: Results from the updated circuits reasoning reversal task with correct answers in bold. Correct forward and forward 2 was the brightness of bulb D increased. Correct reverse was the switch was opened.

While it appeared that students were well equipped to give correct answers to all of the versions, their chains of reasoning were found to be lacking. All of the questions yielded either one or two students with correct reasoning chains despite the large number of students who answered correctly, suggesting the correct answers on this task can overwhelmingly be found through incorrect ideas.

	Forward (N=63)	Forward 2 (N=64)	Reverse (N=66)
Correct Reasoning	5%	5%	3%
Incomplete Correct Reasoning	3%	3%	3%
All Current to D (implicit assumption of constant current through battery)	49%	66%	65%
Ohm's Law (current through battery and current through bulb D confusion)	17%	23%	15%
Independent Branches	13%	0%	0%
Switch Confusion	10%	2%	9%
Other/Unclear	3%	2%	5%
No Reasoning	0%	0%	0%

Table 8: Results highlighting different chains of reasoning for updated circuits task.

The constrained forward and the original forward are similar except for three categories, reasoning chains related to the remains the same option and all current to bulb D. Essentially, the difference in percentages in the three categories were all accounted for without considering other categories. This suggests that the people who would have concluded that there was no change in the circuit were constrained from selecting that answer and instead focused on the current no longer deviating before bulb D when the switch was opened. This was backed up by the results from the reverse version where the reasoning category percentages were almost identical to those of the constrained forward version. The comparison between the constrained forward and reverse suggests that the differences in reasoning chains were due to the constraints associated with the question format and not due to the direction of the questions.

DISCUSSION

The most exciting trend in the data arose with the three blocks questions, specifically the updated version. It could clearly be seen that the students responding to the reverse task were more often able to construct lines of reasoning that were considered satisfactory. By having the constrained forward version with restricted answer choices, the comparison between the updated forward version and reverse version was more easily interpreted due to the reasoning chains being similar between the two. This led to direct comparisons without the need to interpret the remains the same lines of reasoning, which weren't seen in the reverse version.

The updated circuits question didn't indicate an improvement in the prevalence of correct reasoning regardless of question direction or constraint. The constrained forward version and the reverse version yielded almost identical percentages of reasoning chains utilized by students, suggesting that directionality doesn't affect which reasoning chains are used. While the directionality of the question didn't affect the reasoning chains, the constraints of the questions did, suggesting that the constraint on answers was the limiting factor.

The two questions highlighted the importance of considering multiple areas of introductory physics where the results of one task didn't match the results of another. The next step might involve think-aloud interviews where all aspects of student reasoning can be heard, leading to a better understanding of what the student is concluding. Also, designing new questions in other contexts could be useful since we found conflicting results with the two contexts studied here. Other improvements could involve the implementation of screening questions to ascertain whether or not the students have the ability to answer a question regardless of reasoning. This might lead to more complete reasoning chains, which would be more useful for analysis.

The implications of this study with regards to teaching are numerous where, in my opinion, the most important pertain to question design for examinations. We found the majority of students selecting the correct answer used incorrect reasoning for the questions about Kirchhoff's laws, which might lead educators to conclude that their students understand the material if administered as part of a multiple-choice test. Another aspect to consider would be how the constraints of a question (*i.e.,* how many answer choices are available) affect the ability of students to use certain lines of reasoning. Also, if an educator chooses to use multiple versions of an examination, they might assume their questions are similar enough to not give advantages or disadvantages, but in some contexts, the similarities might not be sufficient to ensure similar performance. The Newton's second law question highlighted just that, where the two seemingly similar questions led to significantly different levels of correct reasoning depending on the direction of the question.

CONCLUSION

Reasoning reversal tasks were designed to test whether the directionality of a question would affect the chains of reasoning used by students. The results from this study suggest that in certain contexts, students could be more successful in constructing correct reasoning chains in one direction than in the other. In other contexts, the difference in reasoning chains was due to question constraints instead. This context-dependence suggests that contextual features and the nature of the lines of reasoning involved may impact which questions exhibit performance differences based on directionality. Moving forward, further testing with a greater variety of questions is necessary in order to arrive at more concrete claims about the reasoning reversal tasks. In addition, more work is needed to determine the mechanism behind any directionality-based performance differences on forward-reverse tasks. Given that the same conceptual understanding is required for reasoning in both directions, it is likely that the identification of relevant mechanisms will provide greater insight into the nature of student reasoning.

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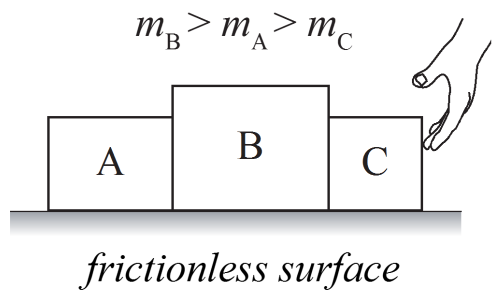
APPENDICES

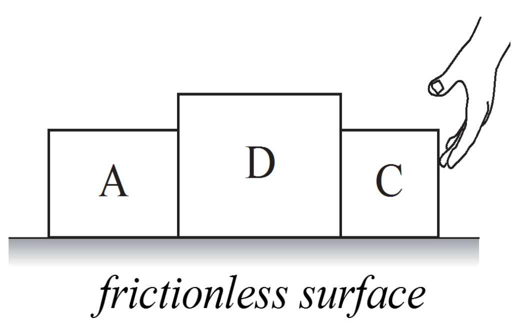
APPENDIX A

<u>Newton's Laws: Three Blocks Forward</u>

Blocks A, B and C are being pushed to the left across a frictionless table by a hand exerting a constant horizontal force. The three blocks have different masses, with $m_B > m_A > m_C$.



Block B is now replaced by block D, which has a mass much greater than the mass of block B. *The hand is still pushing with the same constant force.*

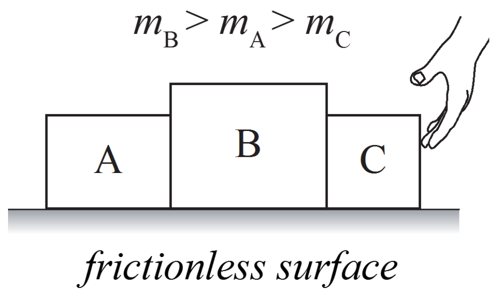


Has the magnitude of the net force on block A *increased, decreased,* or *remained the same* after block B is replaced with block D? Explain.

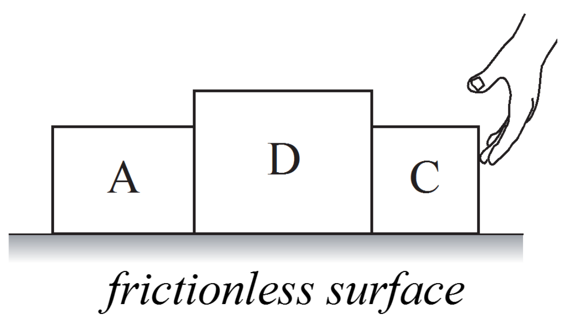
APPENDIX B

Newton's Laws: Three Blocks Reverse

Blocks A, B and C are being pushed to the left across a frictionless table by a hand exerting a constant horizontal force. The three blocks have different masses, with $m_B > m_A > m_C$.



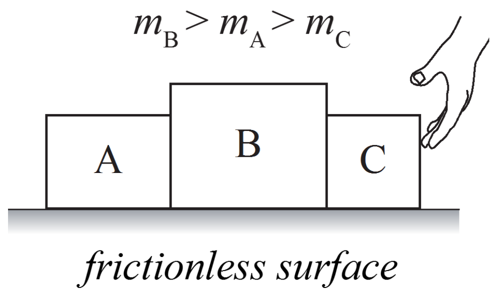
Block B is now replaced by block D, which has a *different* mass, but *the hand is still pushing with the same constant force*. After the change, it is observed that the magnitude of the *net force* on block A has decreased.



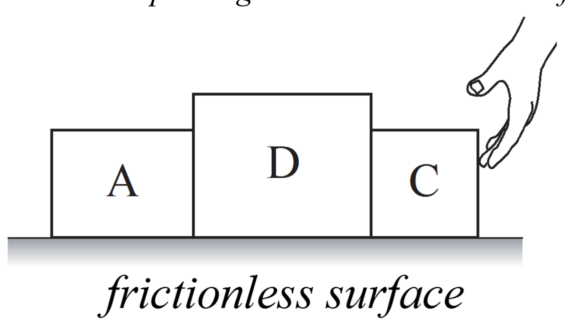
Is the mass of block D *greater than* or *less than* the mass of block B? Explain.

Newton's Laws: Three Blocks Forward 2.0

Blocks A, B and C are being pushed to the left across a frictionless table by a hand exerting a constant horizontal force. The three blocks have different masses, with $m_B > m_A > m_C$.



Block B is now replaced by block D, which has a mass much greater than the mass of block B. *The hand is still pushing with the same constant force.*

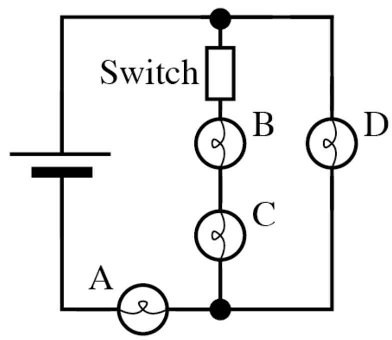


Has the magnitude of the net force on block A *increased* or *decreased* after block B is replaced with block D? Explain.

APPENDIX D

Kirchhoff's Circuit Laws: Bulb Brightness Forward

All of the bulbs in the circuit at right are identical. Assume that the battery is ideal. The switch is initially *closed.*

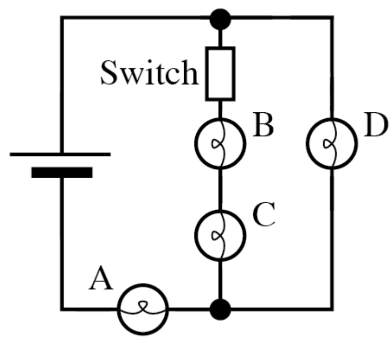


The switch is now opened. Does the brightness of bulb D *increase, decrease,* or *remain the same* upon opening the switch*?* Explain your reasoning.

APPENDIX E

Kirchhoff's Circuit Laws: Bulb Brightness Reverse

All of the bulbs in the circuit at right are identical. Assume that the battery is ideal. It is unknown whether the switch is initially open or closed.

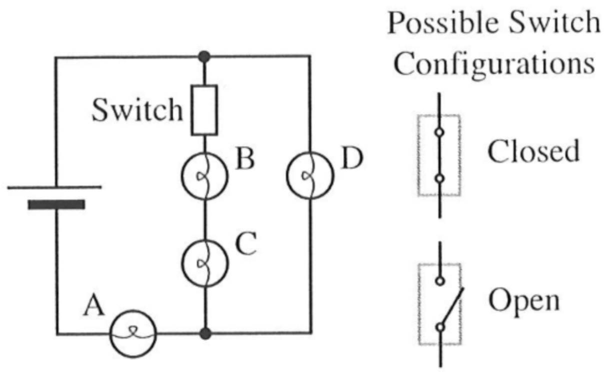


A change is made to the position of the switch and it is observed that the brightness of bulb D *increases* as a result of the change. Did the change involve *opening* or *closing* the switch? Explain your reasoning.

APPENDIX F

Kirchhoff's Circuit Laws: Bulb Brightness Forward 2.0

All of the bulbs in the circuit at right are identical. Assume that the battery is ideal. The switch is initially *closed.*



The switch is now opened. Does the brightness of bulb D *increase* or *decrease* upon opening the switch? Explain your reasoning.

The switch diagram above was also used for both the forward and reverse versions of the circuits question the second time it was run.

AUTHOR'S BIOGRAPHY

William (Will) S. Johnson was born in Montpelier, Vermont on December 22, 1994. He and his family moved frequently in his childhood until 2004 where they settled in East Montpelier, Vermont where he graduated from U-32 High School in 2013. Originally majoring in engineering physics, Will switched to physics in his senior year after realizing that he wanted to pursue teaching after graduation. He plans on moving back to Vermont in his pursuit and will look towards a masters in education after working for a period.