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The Impact of Just-In-Time Prompts in Student Usage of Unit Checking

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ABSTRACT

The use of dimensional checking of answers is inherently useful in introductory physics courses, but only if students are able and choose to implement this kind of check. An analysis of homework answers from introductory physics courses showed that many students submit responses with incorrect dimensions on their assignments, and these responses cannot possibly be correct. There have been interventions created to mediate this issue, but they often require significant class time and effort. We propose a simpler and less time-intensive approach: 'just in time' prompting of dimension checks embedded into homework assignments. To test this intervention's effectiveness, students were randomly assigned variations of homework questions that were either modified with a prompt or left unchanged and were then asked if they had checked their dimensions at any point while solving the problem. It is still unclear if this intervention works and how effective it could be, as it was more effective for some problems than others. Though some positive impact was observed, future research regarding the effects of this 'just in time' prompting could be beneficial for students in introductory physics courses.

TABLE OF CONTENTS

List of Figures iii

List of Tables iv

Acknowledgements v

Chapter 1 Introduction 1

- 1.1 Previous Interventions 3

Chapter 2 Analysis of Dimensions and Correctness 6

- 2.1 Catch a Bus 6
- 2.2 Rotating Wheel 7
- 2.3 Maximum Height 8
- 2.4 Block Velocity 9
- 2.5 Horizontal Force 10

Chapter 3 Prompting and its Effects on Student Unit Checking 13

- 3.1 Maximum Force 14
- 3.2 Sliding Block 15
- 3.3 Ballistic Pendulum 17

Chapter 4 Conclusions 20

Bibliography 21

LIST OF FIGURES

Figure 1. Diagram for the horizontal force problem.. 10

Figure 2. Diagram for the maximum force problem.. 14

Figure 3. Diagram for the sliding block problem 16

LIST OF TABLES

Table 1. Dimensions and Correctness Results from Mastering Physics................................ 11

Table 2. The Maximum Force Problem Results.. 15

Table 3. The Sliding Block Problem Results... 17

Table 4. The Ballistic Pendulum Problem Results (1) 18

Table 5. The Ballistic Pendulum Problem Results (2) 19

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Chapter 1

Introduction

Anyone who has taken an introductory physics course has likely been told to check the units or dimensions of their answer. A dimension is a fundamental aspect of a physical quantity, indicating what it is a measure of, for example length, mass, or time. A quantity is defined as having a unit "when we have an operational definition for assigning a number to it and that the number that results depends on the choice of an arbitrary standard" [1]. For example, a length of 1 meter can also be defined as 100 centimeters, and the choice of which unit to use does not change the length. Units, such as meters, kilograms, or seconds, are the base units of dimensions.

Many physics problems can be worked through symbolically, and operations such as addition and multiplication can be performed on quantities with dimensions and units. For the purposes of this study, dimensions are called "incorrect" when the dimensions of a quantity do not match the dimensions of the desired quantity that is being computed. Dimensions are called "inconsistent" when the expression involves the addition or subtraction of dimensions that are not the same. For example, an expression where dimensions of mass are being added to dimensions of speed would have inconsistent and incorrect dimensions. Giving an answer with dimensions of speed when dimensions of acceleration are required would have incorrect dimensions. By these definitions, an expression with inconsistent dimensions will always have incorrect dimensions.

To correctly answer a physics problem, the student's answer must have the correct dimensions. Checking the dimensions of an answer is a relatively simple way to get some indication if the answer is incorrect. However, correct dimensions do not always indicate a correct answer, as the student may have added an additional numerical multiplier that leads to an incorrect answer. Although this strategy has value for students, they often omit units when substituting their numbers into an equation, and this no longer allows them to use unit checking as a way to gain confidence in their answer [1].

There are many ways to check the dimensions of an answer. The most common checking method involves substituting the fundamental dimensions of the quantity represented by each symbol and making sure both sides have the same dimensions attached to the quantity [2]. This can be done by, effectively, "canceling out" dimensions that are present in both a numerator and denominator on one side of the equation to simplify. Students can also perform a similar procedure with units or even compound dimensions, such as force or energy, though this is much less common [2]. Dimension checking is not the only solution evaluation strategy that students can employ to confirm their answers; however, it is one of the easiest to perform and often catches errors. Despite the obvious benefits of dimension checking, and the fact that students are able to identify its value, students do not often check the dimensions of their answers.

Though dimension checking is not as common as it should be, it is often found to be the most common form of checking. Dimensional checks were found to be employed more than all other sense-making strategies, such as evaluating limiting and special cases [2].

1.1 Previous Interventions

There have been many interventions created to study unit and dimension checking within undergraduate physics courses. One such study involved giving students two different problems: the “ladder problem” and the “shelf problem”. Each participant in the study saw one version of each problem in one of two formats: the “verify” format and the “contrasting cases” format. In the verify format, solutions to the problem with two mistakes were presented and the participants were asked to verify the correctness of the dimensions and angular dependence of the expression. The solution given, along with the correct solution, was used in the contrasting cases format. This format required the participant to identify which answer was correct, if any. Each response was then coded according to checking strategy and accuracy of the attempted strategy. Between both the shelf problem and the ladder problem, unit checking was used more frequently in the verify case, though it was not always employed correctly [3].

In another study, a series of tasks were created to help students learn unit analysis and special-case analysis. These tasks were included in homework and recitation activities and were evaluated on a rubric with a scale from zero to three, based on attempt and understanding of the strategy employed. This study compared two courses, one of which explicitly modeled unit analysis in the course. One evaluation activity was then included on each of the six exams in both courses. The results from the activities on the exams show a decreased use of unit analysis after the second exam, though this could possibly be attributed to the increased proportion of special-case analysis after that exam, which helped students improve their understanding of that strategy while decreasing their use of unit analysis [4].

Another study was conducted in a similar fashion. In the course being studied, the instructor specifically emphasized solution checking and three exercises were administered and collected on days one, eight, and twenty. These exercises each contained two layers, and layer one was turned in before the students were able to see layer two. Layer one consisted of four algebraic formulas and students which was most “plausible” and to explain their choice. In layer two, the students were given a solution to the same problem and instructed to "Check to see if this formula is sensible in as many ways as you can think of, explaining your thinking clearly." Layer two was more consistent and more informative, so only layer two was used for coding. Rather than assess the checks on a scale from zero to three, the use of the checks was evaluated only on whether they were attempted or not. An incorrect or incomplete attempt of a unit check would be evaluated the same way as a correct and complete one. In the course being evaluated in this study, however, all the checks that were being studied were continually used in class, so there was no observed decline in the use of any of them. Unit checks were found to be the easiest check for students to employ [5].

A fourth study was conducted in which students were given homework assignments containing two to four problems with anywhere from two to ten embedded sense-making prompts. On the first three homework assignments, students were instructed to use specific sense-making strategies in the sense-making prompts. On the subsequent homework assignments, which are the assignments this study analyzed, the prompts became more open-ended and general. Like the previous two studies, this study found that dimension checking was the most common strategy employed, with the overwhelmingly most common method being the substitution of fundamental dimensions into the expression.

These studies have a few commonalities: they were conducted with relatively few data points and the tasks the participants were completing were designed for the specific purpose of studying unit and dimension checking. Additionally, in some of these studies, there was explicit course instruction related to dimensions and other solution-checking strategies.

While it is important to ensure students are checking their answers to physics problems, going over these strategies in class may not be the most efficient use of class time. It may be possible to effectively encourage students to check their solutions though other methods that are much easier to implement, including prompting on homework assignments.

Chapter 2

Analysis of Dimensions and Correctness

The data for this phase of the study was obtained from Pearson's Mastering Physics and parsed using python scripts. The data was from five symbolic problems on Pearson's Mastering Physics homework platform, which is an online platform designed to help students learn introductory physics through tutorials, an electronic textbook, and videos. A symbolic problem is a problem in which the answer is not numerical, but a combination of given symbols, which makes it possible to interpret the dimensions of a given expression because each symbol has predetermined units.

All five problems were related to general mechanics, and they were not specially designed for dimension checking; they were just the homework problems already assigned to students though the Mastering Physics platform.

2.1 Catch a Bus

The first problem, which will be referred to as the "catch a bus" problem, had 26641 total responses, 21865 (82%) of which were able to be parsed. The catch a bus problem describes a situation in which a man is running at a constant speed, v_{man}, to catch a bus that is already at a stop. At time zero, the man is a distance, d, from the door of the bus. Also at time zero, the bus begins to move with a positive acceleration, a_{bus}. The first part of this question asks the student to determine the position of the man as a function of time, and the second part asks the student to determine the position of the bus as a function of time. The third part of the question was multiple choice and asks the student to choose which condition needs to be met for the man to catch the bus, in terms of the magnitude of the position of the man and bus at time t_{catch}, which is when the man reaches the bus, v_{man}, and a_{bus}. The fourth part of the problem, which is the part of the problem that was used for this study, asks the student to find the minimum v_{man} where the man will catch the bus in terms of a_{bus} and d. In the last part of the problem, the man meets the bus, but misses getting on it. This part asks the student if the man will be able to catch the bus again if he keeps running at the constant v_{man}.

The complete correct answer for the value of the minimum v_{man} is $\sqrt{2a_{bus}d}$, which has dimensions of velocity, which makes sense because the problem is asking for a minimum velocity. If the student's response did not have dimensions of velocity, that should serve as indication for them to check their work. Some of the most common incorrect answers were $2a_{bus}d$, which has dimensions of velocity squared, $\sqrt{a_{bus}d}$, which has correct dimensions but is missing the $\sqrt{2}$ multiplier, $\sqrt{2a_{bus}}d$, which, again, has incorrect dimensions, and $a_{bus} + d$, which has inconsistent dimensions of acceleration and length.

2.2 Rotating Wheel

The second problem, referred to as the "rotating wheel" problem, had 273573 total responses, 258216 (94%) of which were able to be parsed. In the rotating wheel problem, there is a solid cylinder with uniform radius, r, and a uniformly distributed mass, m. This wheel is pivoted on a stationary axle through its axis and rotates at a constant angular speed, rotating n full revolutions in a time interval, t. The student is then asked to find the kinetic energy of the rotating wheel in terms of m, r, n, t, and π. The correct answer to this problem is that the kinetic energy of the rotating wheel is $\frac{1}{4}mr^2(\frac{2\pi n}{t})^2$. When the dimensions of the variables are combined, the overall expression does have the required dimensions of energy. In this problem, some of the most common incorrect answers were $\frac{1}{2}mr^2(\frac{2\pi n}{t})^2$, which has correct dimensions with an incorrect numerical multiplier, $\frac{1}{2}\frac{\pi nmr^2}{t}$, which has the incorrect dimensions of energy×time as well as some incorrect numerical multipliers, and $\frac{1}{2}mr^2(\frac{\pi n}{t})^2$, which also has correct dimensions with an incorrect numerical multiplier.

2.3 Maximum Height

The third problem, the "maximum height" problem, had 140924 total responses, 84715 (60%) of which were able to be parsed. This problem states that a projectile is launched with a speed v_0 and angle θ and asks the student to derive an expression for the maximum height, h, of the projectile in terms of those two parameters and appropriate constants. The correct answer is that the height is $\frac{(v_0 \sin\theta)^2}{2g}$, where g is the gravitational constant on Earth, which has dimensions of acceleration. In the correct expression, the overall dimensions are a length, which makes sense because the problem asks the student for the maximum height of a projectile. The incorrect submissions for this problem had a very high rate of incorrect dimensions, and some of the most common incorrect answers were $v_0 \sin\theta$, which has dimensions of velocity, and $v_0{}^2 \sin^2\frac{\theta}{2g}$, which has both incorrect and inconsistent dimensions, though the reasons the dimensions are inconsistent may not be obvious. Trigonometric functions can only operate on dimensionless quantities to result in dimensionless quantities, and $\frac{\theta}{2g}$ has dimensions of inverse acceleration, making the units inconsistent with the use of the sine function.

2.4 Block Velocity

The fourth problem, the "block velocity" problem, had 7658246 total responses, 5974691 (78%) of which were able to be parsed. In the block velocity problem, a block of mass m is at rest at the origin at t=0. It is then pushed with a constant force F_0 from $x = 0$ to $x = L$ across a horizontal surface with a given coefficient of kinetic friction, $\mu_k = \mu_0(1 - \frac{x}{L})$. The first part of the problem asks the student to use the chain rule to find an alternative definition for the acceleration, a_x, which can be written in terms of v_x, the block velocity, and $\frac{dv_x}{dx}$. In the second part of the problem, the students are expected to use this to find the velocity of the block at position L in terms of L, F_0, m, μ_0, and appropriate constants. The correct answer to this problem is that the velocity is $\sqrt{\frac{2F_0L}{m} - g\mu_0L}$. The dimensions of each part of this answer can be determined individually to ensure that the two are compatible with each other. Both parts should have the desired dimensions of the final answer, which is velocity, and they do. The numerical multipliers, square root, and subtraction make this problem very easy to answer incorrectly. Some of the most common incorrect answers were $\sqrt{\frac{F_0L}{m} - \frac{\mu_0 gL}{2}}$, which has correct and consistent dimensions, though there are also some out of place numerical multipliers, $\sqrt{\frac{2F_0}{m} - \mu_0L}$, which has incorrect and inconsistent dimensions of velocity and length, and $\frac{F_0}{m}$, which has incorrect dimensions of force/length.

2.5 Horizontal Force

The fifth and final problem, the "horizontal force" problem, had 94778462 total responses, 67045296 (71%) of which were able to be parsed. In the horizontal force problem, the student is shown Figure 1 and asked to solve for the magnitude of force *F* required so that m_1 does not slip down the wedge. They are also told to assume all surfaces are frictionless.

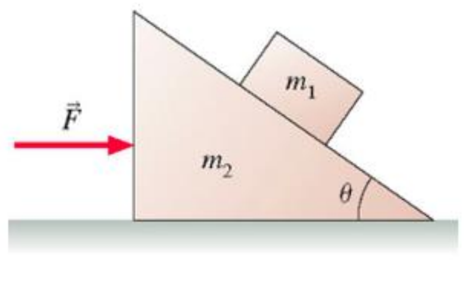

Figure 1. Diagram for the horizontal force problem

The correct answer to the horizontal force problem is that the force is $(m_1 + m_2)gtan(\theta)$, which results in dimensions of force. Some of the most common incorrect responses to this problem were $m_1 g \sin\theta$, which has correct units, but is missing the dependence on m_2 and contains the incorrect trigonometric function, 0, which has no units, and was categorized as incorrect, and $m_1 + m_2$, which has the incorrect units of mass and is missing the angular dependence.

Each answer to each problem was categorized by answer correctness, dimensional correctness, and dimensional consistency. The only responses considered for this analysis were those that the python script was able to parse. Each response was analyzed based on three attributes: the correctness of the response, the correctness of the dimensions of the response, and the consistency of the dimensions of the response. Table 1 shows the percentage of incorrect answers, and the percentages of incorrect answers that have both incorrect and inconsistent dimensions.

Table 1. Dimensions and Correctness Results from Mastering Physics

Problem Number	1	2	3	4	5	Average
A) % incorrect responses	30	49	54	60	40	47
B) % A with incorrect dimensions	82	53	74	73	46	72
C) % A with inconsistent dimensions	24	3	17	52	7	21

There is a great deal of variability between individual problems, but it is evident that many students are submitting answers to Mastering Physics with incorrect dimensions. Theoretically, an average of 72 percent of incorrect responses could be eliminated if students eliminated calculated answers with incorrect dimensions, because they physically cannot be correct. Solution checking would not only improve students' grades in these courses, but it would allow students to go back and check their work for errors, so they are able to understand where they erred and to correct it rather than entering an incorrect solution and going immediately to the next problem.

Rather surprisingly, the questions with the highest rates of incorrect answers having incorrect dimensions were the catch a bus problem, the maximum height problem, and the block velocity problem, while the rotating wheel and horizontal force problems had lower rates of incorrect answers having incorrect dimensions. This is interesting because the problems with higher rates of incorrect answers having incorrect dimensions were supposed to result in dimensions of either velocity or acceleration, while the other two problems were supposed to result in dimensions of energy and force, which are compound dimensions. Though it appears that compound dimensions would be more difficult to check, it is possible that students are more frequently missing numerical multipliers or adding incorrect ones, especially because the rotating wheel problem has multiple numerical multipliers with no attached units, such as $\frac{1}{4}$, π^2, and n^2. Additionally, the horizontal force problem requires the use of trigonometric identities, which have no units, creating another way for students to make mistakes that are unrelated to the units of their answer submissions.

There is also high variability between problems in terms of the percentage of total incorrect responses that contained inconsistent units, but, as this is a subset of the responses with incorrect units, there are fewer submitted responses with this particular issue. However, in problem 4, the block velocity problem, these responses with inconsistent dimensions make up a large fraction of those with incorrect dimensions, and over half of the total incorrect responses. Compared to the other problems used for this analysis, the block velocity problem is unique because it involves the subtraction of two quantities, leaving much more room for errors related to inconsistent dimensions.

Chapter 3

Prompting and its Effects on Student Unit Checking

It is evident that many incorrect responses submitted by students on physics problems could be avoided using simple unit or dimension checking strategies. Many interventions exist to get students into this habit, but they often require specialized assessments and use of time in class to discuss answer checking strategies. A possible solution to this problem that is much easier to implement is adding prompting to students' homework problems that encourages unit checking.

In Penn State's PHYS 211 (General Physics: Mechanics) course, students complete their homework using Expert TA, which is an online platform that allows instructors to write and edit homework questions in addition to use of their question bank. The problems used in this study were already included in the assignment by the instructors, but they were edited and pooled. Each selected problem had three versions, each containing two parts. Version one included the question and then asked the students if, at any point in the problem, they had checked that the dimensions of their solution was correct, if they "checked their units". The students were also informed that their answer to this part would not influence their final grade on the assignment. Version two of the question was very similar, but the first part had the added prompt of "please check your dimensions" immediately following the question, and the second part was the same. The first part of version three gave the students the problem statement but asked them to determine and enter the dimensions of the final answer, and the second part is where they were asked to enter their answer to the problem, so they were not explicitly asked if they had checked their dimensions.

3.1 Maximum Force

The first problem used in this phase of the study, the "maximum force" problem, had 1046 total responses. There were 408 responses to version one of the question, 408 to version two, and 411 responses to version three. In the maximum force problem, the student is presented with Figure 2 and asked to find the maximum force that can be applied for the two blocks to move together in terms of variables given in the problem statement and the gravitational acceleration constant, g.

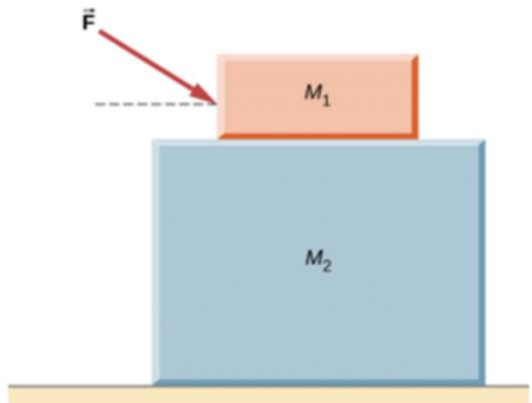

Figure 2. Diagram for the maximum force problem

The correct answer to this problem is that the force is equal to $\frac{\mu m_1 g(m_1+m_2)}{m_2\cos(\theta)-\mu\sin(\theta)(m_1+m_2)}$, which results in dimensions of MLT^{-2}, where M is mass, L is length, and T is time. This combination of dimensions results in the complex dimensions of force, which is to be expected.

This first problem yielded some unexpected results. When the students who received versions one and two of the problem were asked if they checked the dimensions of their solution, 56 percent of students given one claimed to have checked their dimensions, and 50 percent of students given version two said the same. It is entirely possible that students were choosing an answer at random or choosing the answer that they thought their instructor wanted for this part of the question, but the overall rates of incorrect units with incorrect answers has a similar trend.

Table 2. The Maximum Force Problem Results

Version Number	1	2	3
A) % incorrect responses	30.9	29.6	30.2
B) % A with incorrect dimensions	33.3	40.9	31.6

The rates of incorrect responses for all three versions were very similar, but the percentages of incorrect answers with incorrect units was not. Surprisingly, the version with the highest rate of incorrect responses with incorrect dimensions was version two, where students were explicitly prompted to check their units, which seems counterintuitive.

The version of the problem with the lowest rate of incorrect responses with incorrect dimensions was version three, where students were asked to compute the dimensions of the expression. It is worth noting 83 percent of responses to the first part of the question were correct as compared to 70 percent of responses to the second part of the question.

3.2 Sliding Block

The second problem used, the "sliding block" problem, had 1139 total responses, with 379 to version one, 379 to version two, and 381 to version three. In this problem, the students are presented Figure 3 and asked to find the expression for the speed of the block at point B in terms of x and t and the expression for the height, h, of the block so that it is at rest at point C in terms of x, t, and g, the acceleration due to gravity.

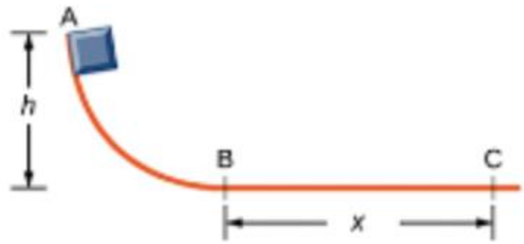

Figure 3. Diagram for the sliding block problem

The first part of the problem, concerning the velocity of the block, was ignored and the second part, regarding the height, h was used. The correct answer for the height of the block such that it would stop at point C is $\frac{2x^2}{gt^2}$, which results in dimensions of L, which is length.

For this problem, 60 percent of students given version one claimed to have checked their dimensions at any point in their calculation, while 58 percent of students given version two said the same. This is the same trend seen in the previous problem, though more students are claiming to check their dimensions overall. Unlike the previous problem, however, the responses to version one of the problem had the highest fraction of incorrect responses with incorrect dimensions, though that version did have the highest rate of correctness. Again, in version three of the problem, there was the lowest fraction of incorrect answers with incorrect units and 84 percent of responses to the part of the question regarding the dimensions were correct.

Table 3. The Sliding Block Problem Results

Version Number	1	2	3
A) % incorrect responses	11.9	14.3	22.3
B) % A with incorrect dimensions	87.5	83.3	81.6

It is also worth noting that many answers were incorrect or had incorrect units due to student misuse of parentheses in this problem.

3.3 Ballistic Pendulum

The third and final problem used in this study, the "ballistic pendulum" problem, was slightly different from the previous two problems. In this problem, a bullet is fired horizontally at a piece of wood suspended on a string and stays lodged in the block after the collision and the whole system swings and reaches a height of h above its initial height. The students are then asked to find the speed of the block/bullet system immediately after the collision, the initial speed of the bullet, and the kinetic energy of the system immediately after the collision.

Version one of this problem is that same as the previous version one: there is no prompting, though students were asked at the end of the problem if they checked their dimensions at any point. In version two a, students were prompted to check their dimensions only on the part of the problem that asked for the speed of the system immediately after the collision, and then were asked if they checked their dimensions at the end. There was no version three of this problem, but in version two b, students were prompted to check their units only on the part of the problem that asked for the initial speed of the bullet, and then were asked if they checked their dimensions at the end.

The results from versions two a and two b were each individually compared to the results from version one for the part of the question that was modified. The correct answers to both parts of the question that were used should have dimensions of velocity, with the correct answer for the speed of the system immediately after the collision being $\sqrt{2gh}$, and the correct answer for the initial speed of the bullet being $\frac{(m+M)\sqrt{2gh}}{m}$, where h is the maximum height above the initial height and m and M are the masses of the bullet and block, respectively.

For the part of the ballistic pendulum problem related to the speed of the system immediately after the collision, there were 354 responses to version one and 353 responses to version two a. For this part of the problem, responses to version one had a higher fraction of correct answers and a lower fraction of incorrect answers with incorrect units. However, only 61 percent of students given version one reported checking their units, while 68 percent of students given version two a reported the same.

Table 4. The Ballistic Pendulum Problem Results (1)

Version Number	1	2a
A) % incorrect responses	95.5	92.1
B) % A with incorrect dimensions	7.9	15.6

The part of the ballistic pendulum problem related to the initial speed of the bullet had 383 responses to version one of the problem and 385 responses to version two b. For this part of the problem, 61 percent of students given version one claimed to have checked dimensions, and 67 percent of students given version two b claimed to have checked, which is similar to the previous part of the problem. Where this part of the problem diverges, however, is in the fact that the percentage of correct answers was higher for version two b and the percent of incorrect answers with incorrect dimensions was much lower than that of version one.

Table 5. The Ballistic Pendulum Problem Results (2)

Version Number	1	2b
A) % incorrect responses	91.9	93.7
B) % A with incorrect dimensions	67.9	31.8

Chapter 4

Conclusions

A large fraction of student responses to introductory physics problems contain incorrect or even inconsistent dimensions. If students were able to eliminate responses with incorrect dimensions, an average of 72 percent of incorrect answers would be eliminated over the five problems used. For some types of problems, this would be more effective than others due to the nature of the solution (whether it contains a sum of quantities with dimensions or more complicated numerical multipliers).

The use of prompting on homework assignments is likely not as effective as was hoped, especially since fewer students claimed to have checked the dimensions of their answer when prompted. This could indicate that students were not answering the question truthfully, but that is still unclear. Even if simple prompting isn't effective, asking students to enter the dimensions of the final answer seems to have a positive effect, though there are too few data points to know this for sure, and more research is required.

It still remains unclear if prompting is a viable option for encouraging students to check their dimensions, though it is obvious that many students are submitting incorrect homework answers that could be eliminated with proper checking of dimensions. More study should be done on how prompting effects students, and interviews with these students to understand how they think about the prompts would be useful.

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