A Demonstration of Kinematics Principles*

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We present a teaching strategy based on showing students a two-part demonstration and asking students to predict the outcome and explain their predictions. Students learn the value of analyzing a situation in terms of basic concepts. They also learn the advantage of simple reasoning over manipulating equations.

Key words: Science Demonstrations, Scientific Reasoning, Teaching Strategies, Secondary School Science, College Science.

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Introduction

In introductory college physics courses, many instructors struggle to get students to put away their formulas — especially the ones they memorized in high school — and to learn to analyze situations before solving problems. In the Physics Education Research Group at the University of Massachusetts, we are particularly interested in helping students learn how to use concepts first, before resorting to equations. We have found several ways to engage students in a manner which stresses conceptual analysis over equation manipulation. One way to do this is by giving comparison problems, in which relationships *might* be used, but computations typically are not. A particularly effective type of comparison problem is one in which any computations that students might be inclined to do are either impossible (e.g., because not enough information is given) or beyond their expertise (e.g., because they must solve a differential equation). Another way to focus students' attention on concepts is to ask students to predict the outcome of a demonstration and to have them explain the reasoning behind their predictions. When the demonstration is counter-intuitive, the resulting discussion is lively and everyone seems engaged in sorting out the features of the demonstration that are relevant for understanding it. A third way of helping students pay more attention to concepts than to superficial features is to extend the context in which the relevant concepts need to be applied. This helps make students' understanding more global and less dependent on the particular circumstance used to introduce concepts.

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For three years, between 1993 and 1996, we used a demonstration of kinematics principles that combines all of these instructional modes. Near the very beginning of the semester, we showed students an apparatus on which two balls will “race” to the end. Students predicted which ball they thought would reach the end of its track first and then explained and discussed their reasons for believing so. After showing this part of the demonstration and finding a suitable explanation, we brought out a second apparatus to see how well students could apply the same concepts to the new situation. After seeing the second part of the demonstration, students failed to find a satisfactory explanation, and consequently they were primed and ready for a short presentation on how to use components of kinematic quantities to understand the outcomes of *both* parts of the demonstration.

Apparatus

There are two separate apparatus needed to do this demonstration. The first is a commercially available apparatus shown in **Fig. 1a**. Two steel balls roll with almost no frictional losses along metal tracks with the same starting and ending points. After going down a short ramp at the very beginning, ball A travels a straight line to the end, while ball B takes a slightly longer path. An important feature of the longer path is the long straight section in the middle.

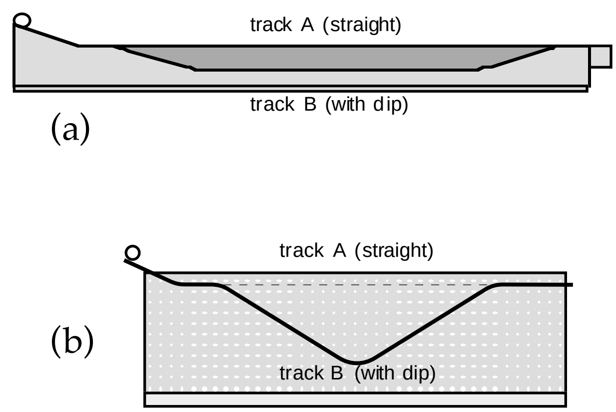

Fig. 1. (a) Commercially available set-up; (b) Home-built pair of tracks using Flex Trak™

The second apparatus is shown in **Fig. 1b**. It is home-built, using Flex Trak™ attached to a peg-board. As with the first set-up, both balls travel down identical short ramps at the beginning. Ball A then travels along a straight, horizontal section to the end, while the ball B follows a noticeably longer path. Note that there is no horizontal section in the middle of the second track. Both balls roll with minimal frictional losses.

Description of Activity and Classroom Results

On the first or second day of class (Introductory University Physics for Math and Science majors), we show students set-up I, explain that we will release both balls simultaneously from the same height, and ask them to predict which ball will reach the end of its track first. Using a classroom communication system,[1] students input their answers. Results are shown in **Fig. 2**. Most students (about 66%) predict that both balls will reach the end at the same time. There are typically three reasons that students give to justify choosing this answer: (1)

Both balls have the same initial and final speeds (by conservation of energy), so they will reach the end at the same time; (2) Ball B goes faster along the horizontal section but travels a longer distance. Ball B gets ahead of ball A along the horizontal section, but A catches up as B rises, so the two balls still get to the end at about the same time; and (3) They guessed. Students picking A usually say that it travels the shorter path, so it gets to the end first.

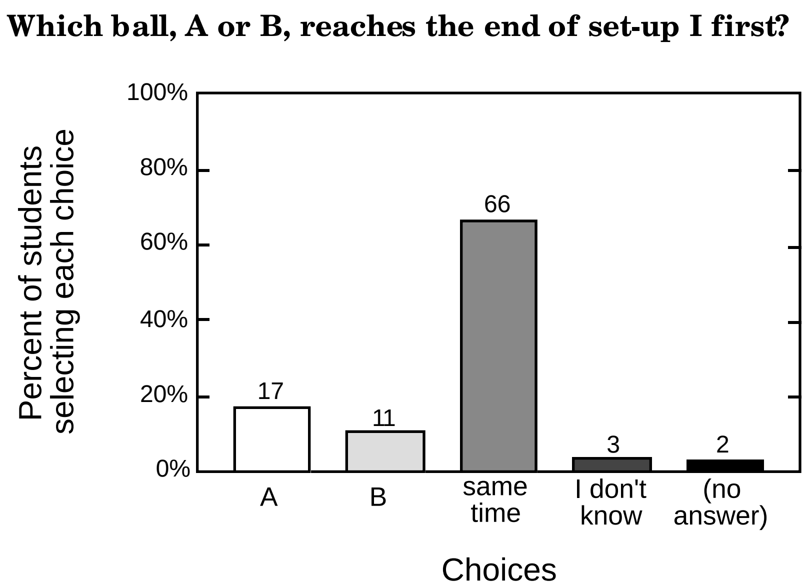

Fig. 2. Predictions for set-up I.

We then show them what happens, and most students are surprised by the result. (Ball B reaches the end first, noticeably sooner than ball A. It usually takes about 1.5 seconds for ball B to reach the end and 1.8 seconds for ball A.) Some students insist on having a classmate release the two balls so that they can be sure that the balls were released at the same time, from the same height, etc. Once students are convinced that what they are seeing is really happening, we explore, as a class, possible explanations of the phenomenon.

The explanation that finally emerges usually goes something like this: "Ball A travels at constant speed for the whole length of the track. Ball B speeds up on the first incline, going faster than ball A on the horizontal portion, and getting far enough ahead of ball A, so that even though it travels a longer distance, it still gets to the end of the track first."

When a majority of students think they understand situation I, we show them the second set-up. There is no horizontal section of track, and the path length is noticeably longer. What do students think will happen in <u>this</u> case? Students' predictions are shown in **Fig. 3**. Each prediction is broken down by what the students chose before seeing the <u>first</u> demonstration. Results are also shown in **Table I**.

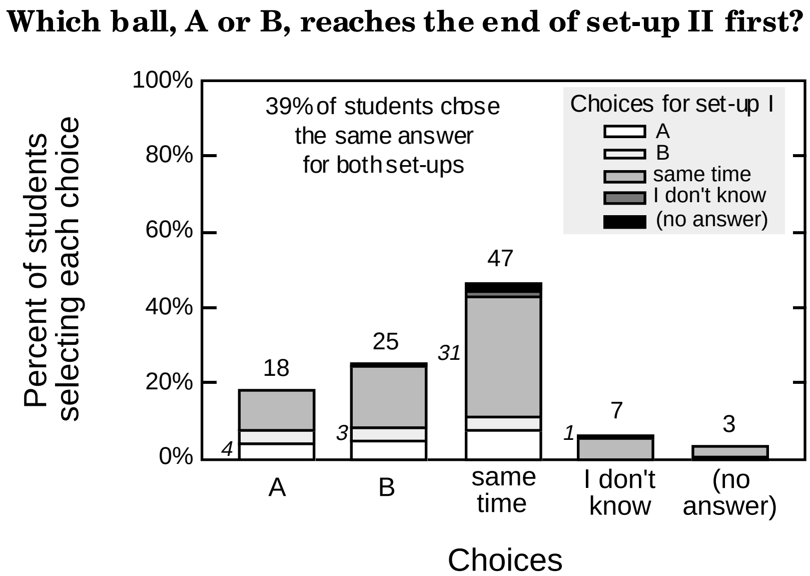

Fig. 3. Predictions for set-up II, broken down by students' predictions for set-up I.

Table I. Percent of students choosing each answer. The correct answer in each case (B) is marked. Percentages of students who chose the same answer for both predictions are shown in italics.

PREDICTIONS FOR APPARATUS I		PREDICTIONS FOR APPARATUS II: A	↓ **B**	SAME TIME	I DON'T KNOW	(NO ANSWER)
TOTALS		**18.0**	**25.4**	**46.7**	**6.6**	**3.3**
A	**17.2**	*4.1*	4.9	7.4	0	0.8
→ **B**	**10.7**	3.3	*3.3*	4.1	0	0
SAME TIME	**66.4**	10.7	16.4	*31.1*	5.7	2.5
I DON'T KNOW	**3.3**	0	0.8	1.6	*0.8*	0
(NO ANSWER)	**2.5**	0	0	2.5	0	*0*

In spite of what they have seen and discussed (or perhaps in part because of it), many students have reverted to their notions prior to seeing the first demonstration. About half of the students (47%) believe that the two balls will reach the end at the same time. And many students (39%) chose the exact same answer that they chose before seeing the first demonstration.

At this point, we show students the second demonstration, and most are truly dumbfounded by the result. (As with set-up I, Ball B reaches the end of the track first.) It seems quite incredible to them that the ball traveling the (much) longer path actually gets to the end of the track first. Typically, the class fails to find a suitable explanation, primarily because their explanation for the first set-up was flawed.

Analysis

Because the balls roll without slipping, energy is conserved, which means that the speed of each ball can be found at any point along its track. Then curvilinear kinematics (i.e., $dt = ds/v$) may be used to find the total amounts of time needed for the balls to complete the different paths. Comparing these times will tell us which ball should reach the end of its track first.

The primary difficulty in applying this procedure is that the shapes of all the tracks need to be determined or approximated before the calculation could be done. (See, for example, "Does Bead B Always Reach *d* First?" by Zheng et al.[2]) Even if we don't do a calculation using curvilinear kinematics, it might seem as though using Conservation of Energy would still be appropriate, at least for the first set-up. The problem here is that the only way to avoid curvilinear kinematics is to ignore what is happening when ball B is on the sloped parts of its track. Also, when we extend the context to set-up II, that explanation doesn't even apply. Using Conservation of Energy focuses attention on the straight horizontal sections of the tracks. The really interesting physics is actually happening while ball B is on the inclines. To understand why, we must analyze the situations in terms of *components* of acceleration, velocity, and displacement. We start with set-up I.

For ball A, after traveling down a short starting ramp, the track is horizontal and the ball's velocity is (very nearly) constant. For ball B, after traveling down an identical ramp, the track is inclined and the ball speeds up. Because the track is straight, the acceleration vector points in the direction of motion, as shown in **Fig. 4a**. The acceleration has a positive horizontal component, which means the horizontal component of its velocity (v_x) is increasing. On the long horizontal section, the velocity is (approximately) constant. As ball B returns to its original height, it slows down and a_x is negative, reducing v_x back to the value it had before

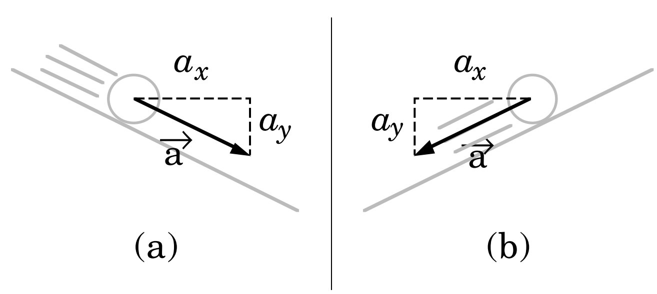

Fig. 4. Diagram showing the acceleration of the steel ball (a) rolling down the incline, and (b) rolling back to its original height.

starting its dip. **Fig. 5a** shows a sketch of v_x vs. t for the two balls traveling along the first pair of tracks.

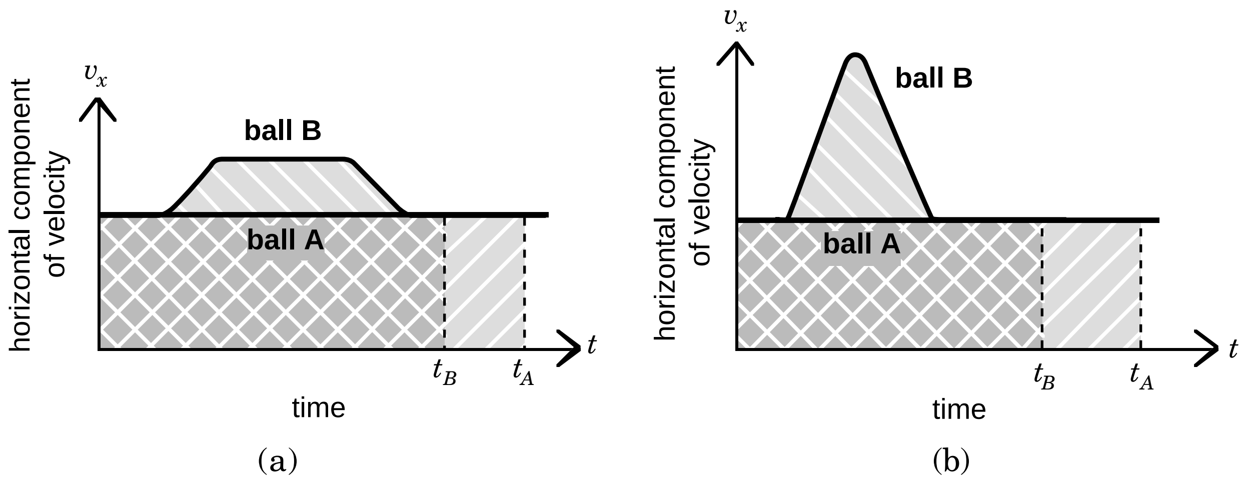

Fig. 5. Sketches of the horizontal component of velocity vs. time for (a) set-up I, and (b) set-up II. Hatched regions represent the displacements of the balls, and cross-hatching indicates intervals when the regions overlap. Labeled are the times at which the balls reach the ends of the set-ups.

The area below v_x vs. t is the horizontal displacement of the ball, so the ball reaches the end of its track when this area is equal to the horizontal distance traveled. Both balls have the <u>same</u> x-component of displacement. This means that the areas of the hatched regions in **Fig. 5a** must be the same. Because v_x for ball B is always greater than or equal to v_x for ball A, ball B will always reach the end of the track first, <u>no matter how long or short the straight, horizontal section is</u> for ball B. <u>As soon</u> as ball B starts down the first incline, it starts to move ahead of ball A. Along the second incline (as in **Fig. 4b**), even though ball B is slowing down, it still has a larger v_x than ball A, and therefore, ball B continues to widen its lead ahead of ball A. <u>At no time</u> does ball A ever move closer to ball B, because at no time does ball A have a larger v_x.

The analysis for set-up II is the same. Both balls speed up along identical starting ramps, they have the same velocity, and they are side-by-side. As ball B travels down the first inclined section, its v_x increases above that of ball A. Along the second half, v_x decreases until it is equal to that of ball A. At no time in between is the velocity constant (although its derivative is zero at the bottom). A sketch of v_x vs. time is shown in **Fig. 5b**.

As before, the horizontal components of the displacements of both balls are the same. Because v_x for ball B is greater than or equal to that of ball A for the entire length of track, ball B must reach the end first.[3]

Confirmation of Analysis

We have found that most people — even experienced physicists — are intrigued by this result, especially for the track without a long horizontal section. For any skeptics who remain, we show in **Fig. 6** a sequence of photographic frames showing the positions of the balls at equal time intervals during the first part of the demonstration. The balls are released simultaneously from rest just before the first frame is taken (**Fig. 6a**). In the first three frames, the balls are side-by-side (though parallax makes it appear as though ball B is lagging behind ball A). Along the first incline, ball B pulls ahead of ball A, so that when ball B reaches its lowest point, it is already ahead of ball A (**Fig. 6d**). Comparing the balls' changes in positions between **Figs. 6f** and **6g**, ball B continues to increase its lead over ball A along the second incline. At no time does ball B have a smaller v_x than ball A.

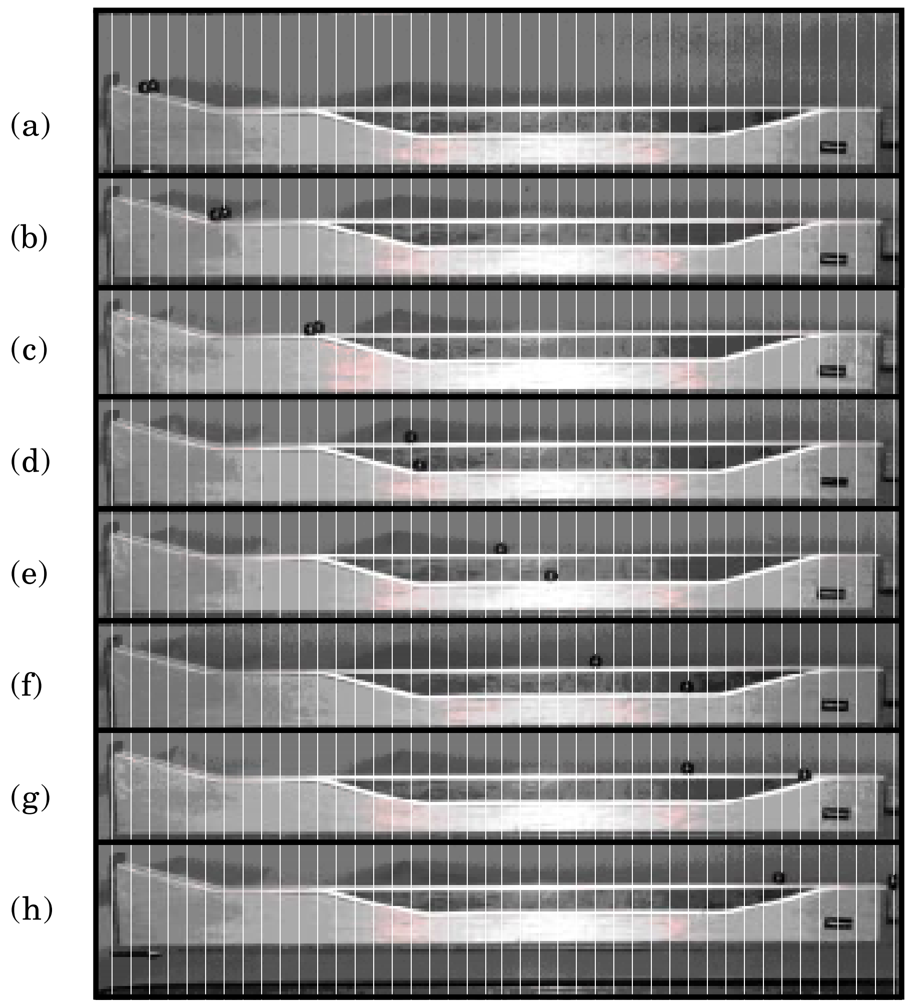

Fig. 6. Photographs of the positions of the two balls at equal time intervals. Both balls are released from rest at the top of the starting ramp just before the first frame is snapped. Subsequent frames are taken approximately every 0.2 sec thereafter, so it takes about 1.5 sec for ball B (lower track) to reach the end, and about 1.8 sec for ball A (upper track). Vertical lines have been superimposed on the photographs to aid in measuring horizontal displacements.

Discussion

We like this activity for several reasons:

- **It engages students.** Students are more self-invested by this sort of activity, because they must cast a vote, one way or another. By being asked to predict an outcome, students must process what they are looking at. Their analysis might be extremely superficial, but at least they are not "withholding judgment" and waiting to see what will happen so that they can "memorize" the outcome, without analyzing it at all. And when the result is counterintuitive, it draws students into the discussion of why it happened.

- **It helps students and teachers to become aware of everyone else's world-view.** When students make predictions, they reveal which features of a physical arrangement they are paying attention to. Students must sort and prioritize the physical characteristics of the arrangement, and they must attempt to apply whatever models they have about how the physical world operates (although they may do this implicitly rather than explicitly). Students become more conscious of their own thought processes and they get to see how other people think about the situation.

- **It encourages students to reflect on, modify, and refine their own mental models of physical phenomena.** Explanations help to uncover implicit models, and help students learn how they think about a situation, so that if their prediction is wrong, they can look for alternate explanations and modify their own thinking.

- **It highlights the value of basic concepts for analyzing situations without the need for sophisticated mathematics.** In this case, students see that an analysis using speed and distance, or conservation of energy, does not give the right result without laborious computations. But focusing on one of the components of acceleration, velocity, and displacement (and thus ignoring the other component) explains the observed result simply and straightforwardly.

- **It stresses the use of graphs to represent and to help analyze physical situations.** In this case, students see the value of a sketch of a component of velocity vs. time. Students see how the area below v_x vs. t means something concrete, and they can reason from the equality of the areas representing equal displacements that the total time of ball B's trip must be less than the total time of A's trip.

- **It involves a comparison rather than a calculation.** All too often, students think they must manipulate equations and determine numerical values to physics problems. To calculate the time needed for each ball to reach the end, we would need to model the situation, make some approximations, and use sophisticated mathematics. But to compare the two times, all we need is some basic concepts and reasoning.

- **It instills some healthy skepticism concerning the value of demonstrations.** As shown by the demonstration of the first set-up, students do not necessarily see what we would like them to see. Their explanations might make sense and fit their observations, but they might not be general enough to be widely applicable. When shown the second set-up, few students were able to analyze it properly. Students and teachers benefit from the realization that demonstrations do not always have the desired effect.

- **It can be done at both the high school and university levels.** Because the activity requires only basic concepts and very little mathematics, it is appropriate for all levels of physics and physical science.

Comments

For those teachers interested in building their own apparatus, there are some important considerations:

• Although frictional losses along the Flex Trak™ are small, they are non-negligible. If the total path length of the inclined parts is too long, then frictional effects will cause ball B to reach the end of its track either at the same time as ball A, or afterwards.

• Another source of energy loss is the lack of rigidity in the Flex Trak™. If the balls are too heavy, the track cannot support them without bending, which causes some damping of the ball's speed. Therefore, the tracks should be as rigid as possible, and the balls should be light enough that the track can support them without visibly sagging.

• The shape of the curved sections of track is very important. First of all, their lengths should be minimized, because it is difficult to use simple reasoning to determine whether a_x is positive or negative while the ball is on them. Secondly, if the radius of curvature is too small, or if the angle of the incline is too large, ball B will slip or possibly even lose contact with the track and will not reach the end of the track first. The radius of curvature should be about two or three times as large as the height of the starting ramp, but no smaller, and the angle of the incline should be about 20° to 25°, but no larger. This will minimize the total length of curved track and should guarantee that the ball will neither slip nor lose contact with the track.

Conclusion

Students benefit from having their attention diverted from equations and computations and re-focused on basic concepts and simple reasoning. We can do this by asking students to make a comparison rather than do a calculation, by asking students to predict the outcome of a demonstration and explain their prediction rather than passively watch a demonstration and listen to an explanation, and by asking students to apply their own ideas to increasingly different contexts rather than limiting them to a narrow one. Not all concepts are applicable in all situations. Conservation of Energy and curvilinear kinematics are extremely useful and powerful, but we usually need sophisticated mathematics and/or simple geometry to apply them to a specific situation. We have shown the power and usefulness of kinematic components and graphs to reason out an answer to a complicated situation. Although we need sophisticated mathematics and physics to actually determine the times needed for two balls to follow different tracks, we can easily <u>compare</u> the times using simpler, more basic concepts and little or no mathematics.

Acknowledgment

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References

1. The classroom communication system is used only to facilitate collection of answers. It is not an essential feature of the activity. Any polling system is fine, as long as every student is required to commit to a prediction and an explanation before seeing each part of the demonstration.

2. T.F. Zheng, K.A. Gonci, M.A. Imparato, C. Ursulet, K. Donovan, & A. Van Heuvelen, *Phys. Teach.* **33**, 376 (September 1995).

3. Note that there are very short, curved sections of each track, on which the acceleration is not parallel to the velocity. We are ignoring these sections.