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Spatial-numeric method application to the movable wedge problem for Physics First pedagogy

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Abstract: The objective is to solve the college physics problem of a block sliding down a movable smooth wedge without friction anywhere using a spatial-numeric perspective. The drawing method used the sum of the normal force and weight of the block to find the wedge acceleration. The drawing method results are equivalent to the algebra method results within drawing accuracy. The result of a geometric construction with regular drawing uncertainly was shown for the case without any horizontal applied force. For the case of a given horizontal applied force, an additional numeric graphing method was shown with additional drawing uncertainty in the result. The geometric construction without graphing resuted in solving the horizontal applied force case via scaling in the concept of modified gravity experienced by the block on the wedge's slant edge, assuming a pre-requisite knowledge of algebra and trigonometry. The presented spatial numeric method and results imply a Physics First pedagogy of using the spatial numeric abilities, with the inclusion of the pre-projectile problem, pre-traffic-light problem, and post-collision problem in a one-semester syllabus.
Keywords: movable wedge; normal force; graphical method; reference frames

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Introduction

The study of cause and effect in terms of force and acceleration (impulse and momentum change) is the essence of Newton's Laws of Motion. However, students struggling to do the force decomposition on inclined planes problem continues to post a pedagogy challenge for instructors (Liu & Mohatala 2021). The student learning difficult of the various types of causal inference relationships in force-acceleration pedagogy (cause to effect, effect to cause, cause to cause) have been examined as well (Jaramillo et al, 2021).

The study of energy is a pillar in physics to account for how things work in mechanics, thermodynamics, electricity and magnetism in introductory physics. In fact, energy instruction has been advocated in middle schools to support learning in college (Nordine et al. 2010). University students' conceptual resources on the understanding energy have been documented (Sabo et al. 2016). The curriculum of energy-first has been implemented with some pedagogical success to the selected first year calculus-based physics (LeGresley et al. 2019).

Given the above pedagogical initiatives on force, acceleration, and energy, the objective of this paper addresses the pedagogy of solving the problem of the normal force in the movable wedge situation in which a sliding object would push a movable wedge to move horizontally with zero friction everywhere, as a compliment solution to the pedagogy of the energy method solution. Although the

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energy method and the Newton's law method in solving the movable wedge problem had been documented by Professor Alpar Sevgen at Bogazici University Turkey (Sevgen, 2013; Sevgen 2014), the use of the spatial-numeric method via geometric construction and graphing would be conducive to the Physics First pedagogy with a minimal knowledge of trigonometry and algebra for beginning science students.

The paper is organized into sections, as follows. The "Normal force and spatial abilities" section serves as a background reminder. The "Methods" section has three sub-sections. "Method 1 sub-section" describes the drawing method for the case of zero applied force and zero friction with the results. The "Method 2 sub-section" describe the drawing method with a small horizontal applied force to the wedge with the results. The "Method 3 sub-section" describes the drawing method of a large horizontal force applied to the wedge with the results. The "Results and Discussion" section describes the incorporation of the movable wedge problem into a whole-semester-syllabus with the pre-projectile problem, pre-traffic-light problem, and post-collision problem in a unified spatial numeric pedagogy. The "Conclusions" section highlights the findings. The purpose is to integrate the spatial numeric method in the Physics First pedagogy, with an immediate objective of fulfilling the gap of solving the movable wedge problem using the spatial numeric method.

Normal force and spatial abilities

The normal force as a component of the contact force is a moderately difficult concept for instructors to teach in the algebra based college physics course for technology students and health science students. The normal force dependence on the geometry in the expression of "weight* cosine" is usually the first example in the incline plane problem, with the "weight*sine" as the acceleration component along the incline. The normal force dependence on the motion in the expression of "weight/cosine" could be the second example in the bank-curve problem. The extension to the conical pendulum example in which the tension of the string becomes "weight/cosine" would be straight forward, although the related problem in the finding of the angle given the length and velocity becomes an involved algebraic exercise. However, the dependence of physics pedagogy on algebra could be alleviated when using graphical solution and geometric construction related to spatial abilities, as reported by us (Dehipawala et al. 2022). The advantageous of the use of the spatial-numeric method in terms of cognitive loading in the solving of physics problems by non-calculus students has been reviewed by us in our 2022 article in terms of the published brain scan data, including the data on physics students and physics professors (Cetron et al. 2019; Cetron et al. 2020; Mason et al. 2021). Recent brain scan studies included MRI visual work form area data, on English-French and English-Chinese bilinguals, which showed the spatial abilities of the linking of character-ideograph processing to facial recognition (Zhan et al. 2023). The decline of spatial ability scores in the studied online cohort in the United States should encourage more spatial-numeric pedagogy, since perceptual intelligence is accepted as being similar to fluid intelligence which uses spatial abilities in the problem solving skills (Dworak et al. 2023). Spatial learning has been traced to the interneurons at receptor level (Zhu et al. 2023), as well as gamma oscillatory neural circuit level (Fernandez-Ruiz et al. 2023). Last but not the least, recent advances in cancer migration studies are incorporating spatial forces visually in the proposed models (Chabache et al. 2021; Javanmardi et al. 2023).

Methods

There are three method sub-sections. Namely, Method 1 for the case of zero horizontal force, Method 2 for the case of a small horizontal force, and Method 3 for the case of a large horizontal force.

Method 1 sub-section: Movable wedge with zero friction

The movable wedge problem is usually solved by using the energy and momentum equations when the applied horizontal force is zero. On the one hand, the analytical solution for the acceleration of the wedge is available on Public Domain such as YouTube (Sevgen, 2013; Sevgen 2014). We have also reported a graphical solution for the easy visualization of the relative velocity concept application to facilitate the energy and momentum calculations (Dehipawala et al. 2022). On the other hand, the movable wedge problem with an applied horizontal force can be solved by using Newton's Second Law, "F = ma" written in algebra and trigonometry format, with the consideration of the normal force dependency on motion. The use of geometric construction to model the normal force in a spatial-numeric method is a necessary complement for conceptual understanding, especially in the Physics First pedagogy, shown in Figure 1.

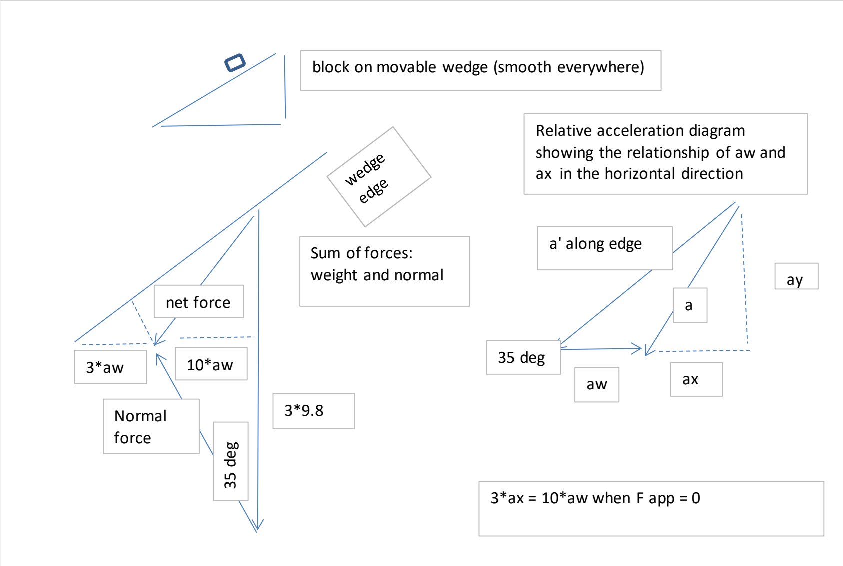


Figure 1. Relationships of forces and relative acceleration, with 3-kg block and 10-kg 35-deg wedge

The 3-kg bock and 10-kg 35-degree wedge were used as the numeric information for easy cognitive load with less algebra symbols. The length of aw represents the acceleration magnitude of the wedge, the length of ax represents the acceleration magnitude of the block horizontally, and the length of ay represents the acceleration magnitude of the block vertically. The geometric construction for the measurement of aw in meter per second per second unit is shown in Figure 2. The case of horizontal F-app can be solved by an additional graphing method without the use of algebra/ trigonometry. Note that the geometric construction in Figure 2 is sufficient to include the horizontal F-app case when using scaling for a modified gravity value with the knowledge of algebra/ trigonometry.

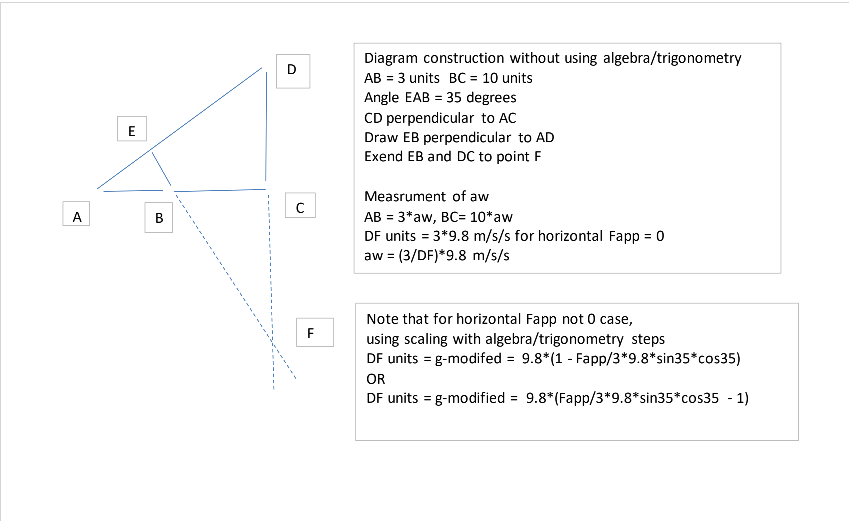


Figure 2. Geometric construction for the measurement of aw in m/s/s unit

Method 2 sub-section: Movable wedge with a small horizontal force

Continuing with the objective of using spatial-numeric method, for the case of a given small horizontal F-app, the relationships of the sum of forces is shown in Figure 3. The derivation of aw in algebra steps supports the scaling discussed in Figure 2. The algebra steps are not necessary in the spatial-numeric method, but the vector drawing in Figure 3 is essential in the conceptual understanding of the sum of forces on an object, the block, and also the wedge. The trivial weight of the wedge and the equal magnitude support force from a presumed table/floor was not shown since the wedge was constrained to move horizontally only.

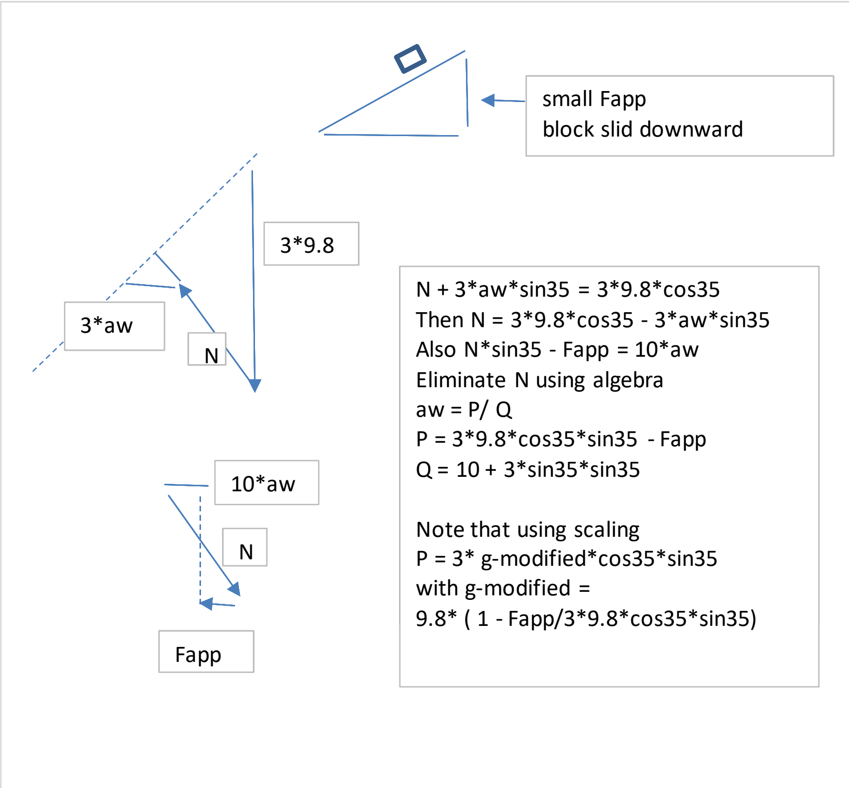


Figure 3. Force diagrams, (3 kg block top), 10 kg wedge bottom), given a small applied force. The trivial weight of the wedge and the equal magnitude support force from a presumed table/floor was not shown

The geometric construction with an additional graphical method is shown in Figure 4, given a small horizontal applied force that the block still slid down the wedge's slant edge. The algebra short cut without using an additional graph shown in Figure 4 could be interpreted as the block experiencing a modified gravity in the scaling concept, in which the F-app is factored into the gravity magnitude yielding a new g-modified value dependent on F-app. In other words, the acceleration the movable wedge with a horizontal applied force can be solved as the acceleration of the movable wedge with zero horizontal applied force in another planet/moon with a modified gravity. However, the cause and effect explanation of the modified gravity is beyond the Physics First pedagogy, but the traditional Algebra First pedagogy in the Physics curriculum requiring algebra as pre-requisite would suffice. When the wedge mass is much larger than the mass of block, the normal force would approach 3*9.8*cos35 with aw approaching 0 m/s/s, that is, the fixed non-movable wedge case. For the case of 3 kg block, 10 kg 35 degree movable wedge, aw = 1.2573 m/s/s. Moreover, a small horizontal applied force pushing to the left on the wedge would nudge the wedge to approach the zero acceleration situation. For a horizontal applied force of 5 Newton, aw would become 0.8022 m/s/s. Returning to the Physics First Pedagogy, the sensitivity of the normal force on the mass ratio (wedge mass/block mass) could be investigated using a graph.

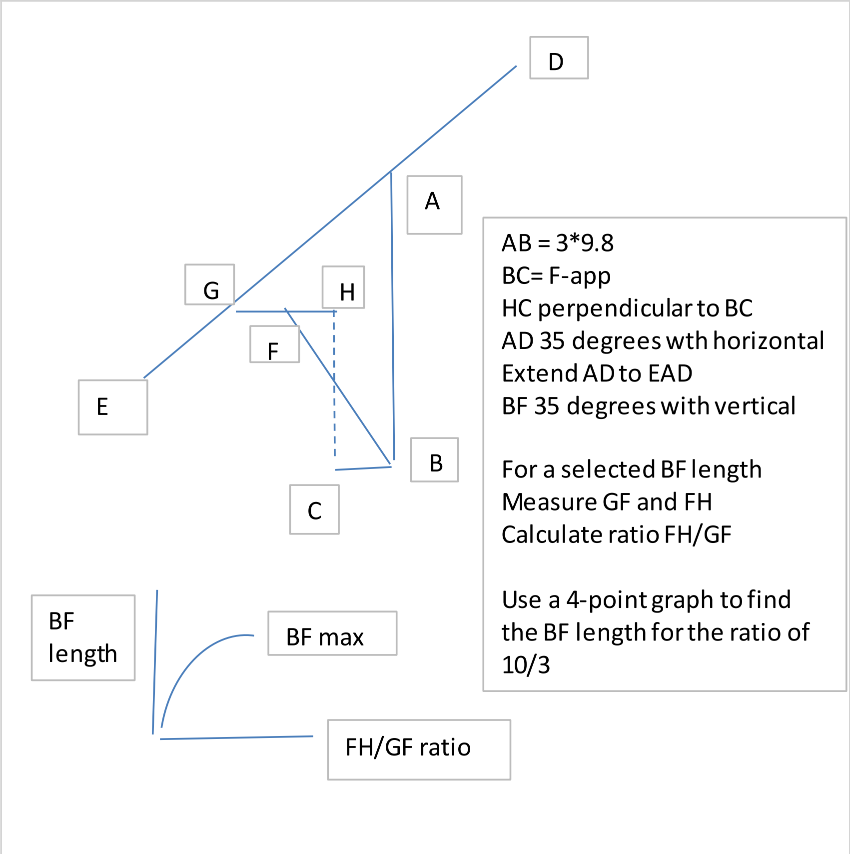
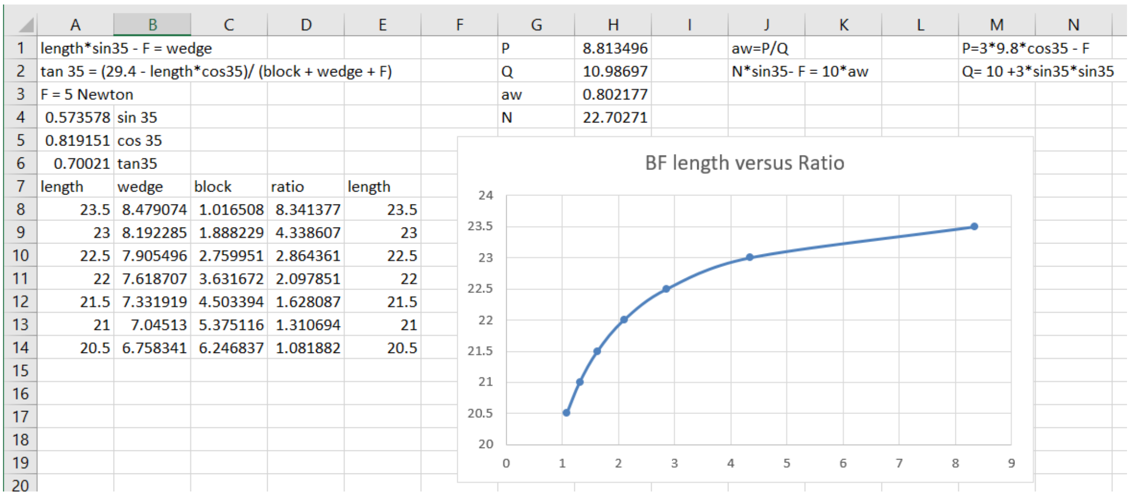


Figure 4. Geometric construction givven a small applied force

A simulation of the graph could asset the extra uncertainty in the spatial numeric method, shown in Figure 5. For F-app of 5 Newton, the BF length that corresponds to a ratio of 10-kg wedge to 3-kg block would be in the region with a slope of about 0.5 Newton per mass ratio in terms of sensitivity. The uncertainty could be reduced when an instructor selects a region with more linearity.



	A	B	C	D	E	G	H	J	M
1	length*sin35 - F = wedge					P	8.813496	aw=P/Q	P=3*9.8*cos35 - F
2	tan 35 = (29.4 - length*cos35)/ (block + wedge + F)					Q	10.98697	N*sin35- F = 10*aw	Q= 10 +3*sin35*sin35
3	F = 5 Newton					aw	0.802177		
4	0.573578	sin 35				N	22.70271		
5	0.819151	cos 35							
6	0.70021	tan35							
7	length	wedge	block	ratio	length				
8	23.5	8.479074	1.016508	8.341377	23.5				
9	23	8.192285	1.888229	4.338607	23				
10	22.5	7.905496	2.759951	2.864361	22.5				
11	22	7.618707	3.631672	2.097851	22				
12	21.5	7.331919	4.503394	1.628087	21.5				
13	21	7.04513	5.375116	1.310694	21				
14	20.5	6.758341	6.246837	1.081882	20.5				

Figure 5. A simulation of BF length usimg F-app = 5 Newton

Method 3 sub-section: Movable wedge with a large horizontal force

For a given large horizontal F-app, the relationships of the sum of forces is shown in Figure 6. The algebra steps in the derivation of aw supports the scaling discussed in Figure 2, and the algebra steps are not required in the spatial-numeric method.

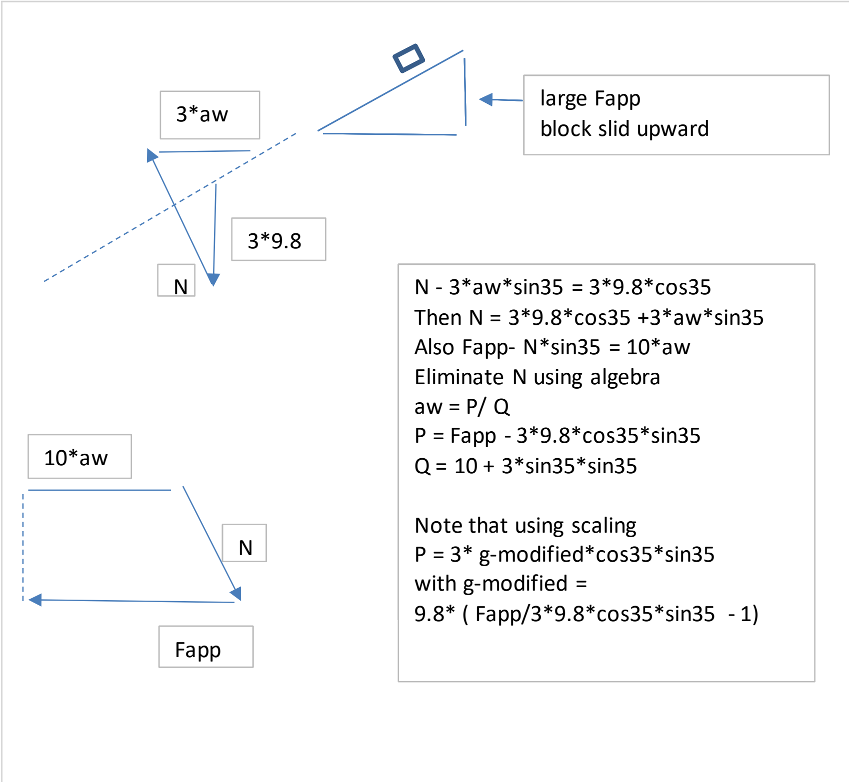


Figure 6. Force diagrams, (3 kg block top), 10 kg wedge bottom), given a large applied force. The trivial weight of the wedge and the equal magnitude support force from a presumed table/floor was not shown

The geometric construction with an additional graphical method is shown in Figure 7, given a large horizontal applied force that the bock would slide up the wedge's slant edge. When the length of BF reaches the minimum, the wedge would not move.

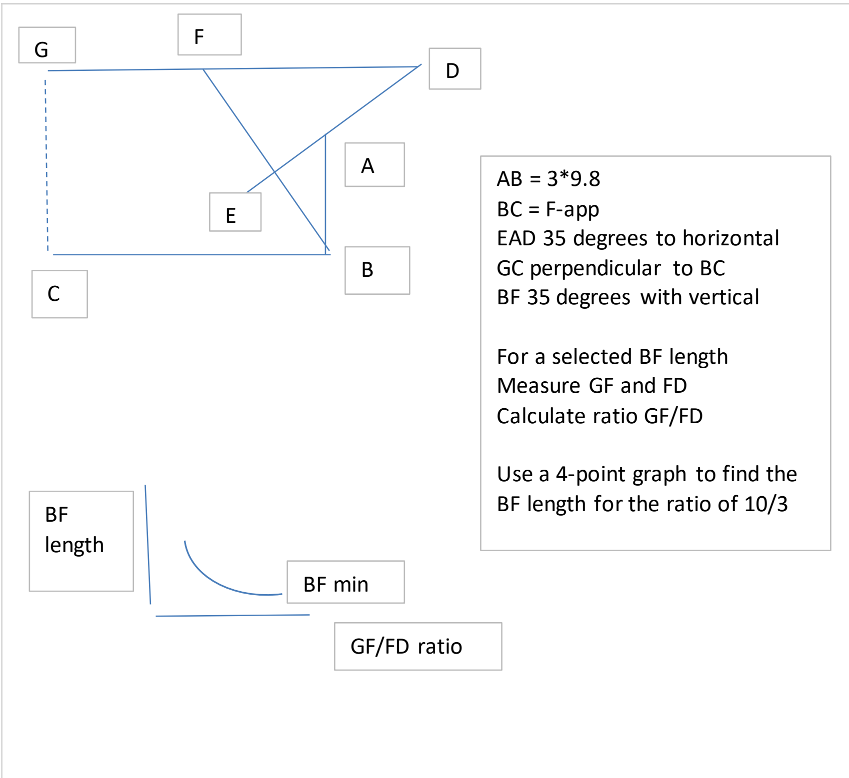


Figure 7. Geometric construction givven a large applied force

A simulation of the graph could asset the extra uncertainty in the spatial numeric method, shown in Figure 8. For F-app of 100 Newton, the BF length that corresponds to a ratio of 10-kg wedge to 3-kg block would be in the region with a slope of about 2 Newton per mass ratio.

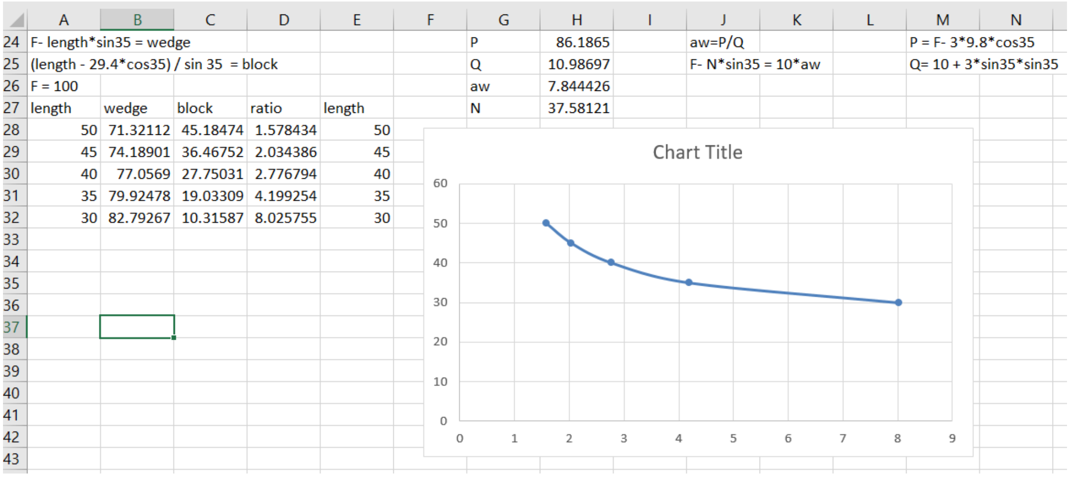


Figure 8. A simulation of BF length using F-app = 100 Newton

A large horizontal applied force would generate a large normal force pushing on the block. The large normal force vertical upward component would overwhelm the gravity downward force, resulting in a vertical upward acceleration, shown in Figure 9, with ay and ax representing the acceleration of the block in the horizontal and vertical directions respectively. The causality in which the large normal force overcoming the gravity force to produce the upward acceleration of the block can be visualized readily, graphically explaining the geometric construction of Figure 7 in terms of cause and effect. The associated algebra steps without the use of the normal force would provide an additional exercise in the Algebra First pedagogy, with less bearing in the Physics First pedagogy.

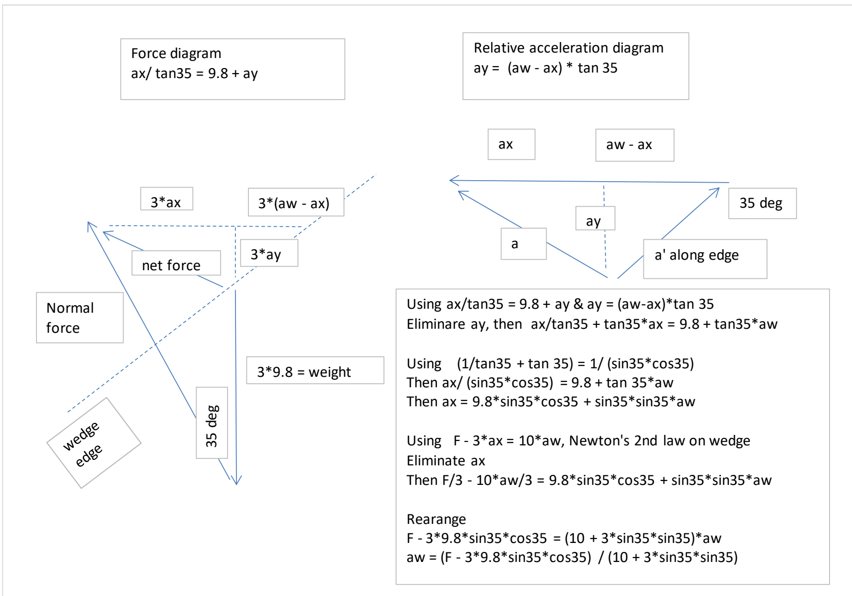


Figure 9. Relationships of forces and relative acceleration, with 3-kg block and 10-kg 35-deg wedge with a large horizontal applied force

Results and Discussion

In order to achieve a holistic approach to the implementation of the spatial numeric method, it is important to develop the numeric spatial anilities throughout a semester in continued learning. Together with fMRI data, it was concluded that spatial thinking has deep connections to math skills

(Hawes et al 2019; Hawes & Ansari 2020), and that a numeral brain region exists for Arabic digits processing in an adult (Conrad et al 2020). A report had suggested the use of eye tracking technology to measure vector drawings in pedagogy delivery (Hoyer & Girwidz 2023). Therefore, it is imperative to develop a collection of problems to foster spatial numeric abilities.

The delivery of the spatial numeric method for the movable wedge problem was embedded between the deliveries of the pre-projectile problem, pre-traffic-light problem, and a post-collision problem. The basketball problem used in class was a standard projectile problem in physics texts such as the Fundamental of Physics by Coletta Second Edition Page 80. A given displacement was used to find the initial speed, shown in Figure 10. The initial velocity vector's angle was varied as 20 + X/2 in which X is the University ID Number last 2-digit (if 00, use the first 2-digit) to encourage individual effort. In a Principles of Physics class of 18 students, mostly with majors in Business and Elementary Education without any algebra pre-requisite courses, 14 students measured the vectors correctly using protractors/rulers and arithmetic in a learning outcome assessment.

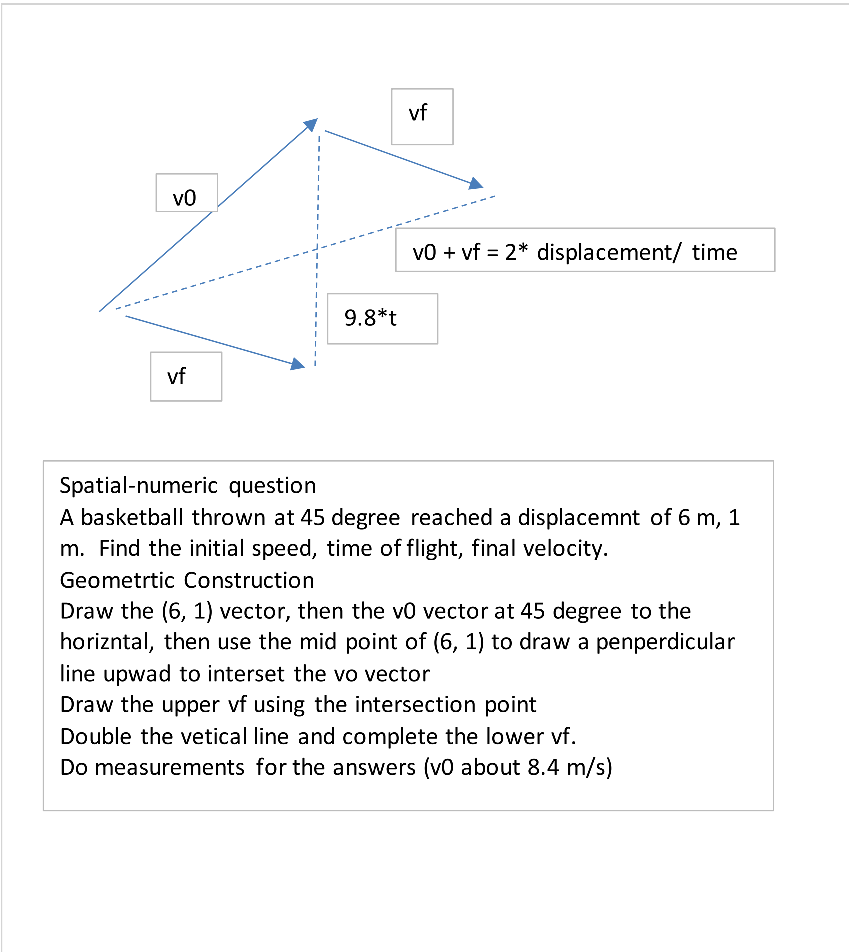


Figure 10. Relationships of vectors in the basketball problem

The pre-traffic-light problem is shown in Figure 11, a standard question in physics texts such as the Fundamental of Physics by Coletta Second Edition Page 100. The traffic-light problem geometric solution is a pre-training for the movable wedge problem. The asymmetry geometric constraints shown in Figure 11 showed the students that the shorter geometric length would entail more tension. In a Principles of Physics class of 18 students, 12 students measured the vectors correctly using compass and protractors/rulers; but only 10 students calculated the ratio values for the tensions correctly in the assessment task.

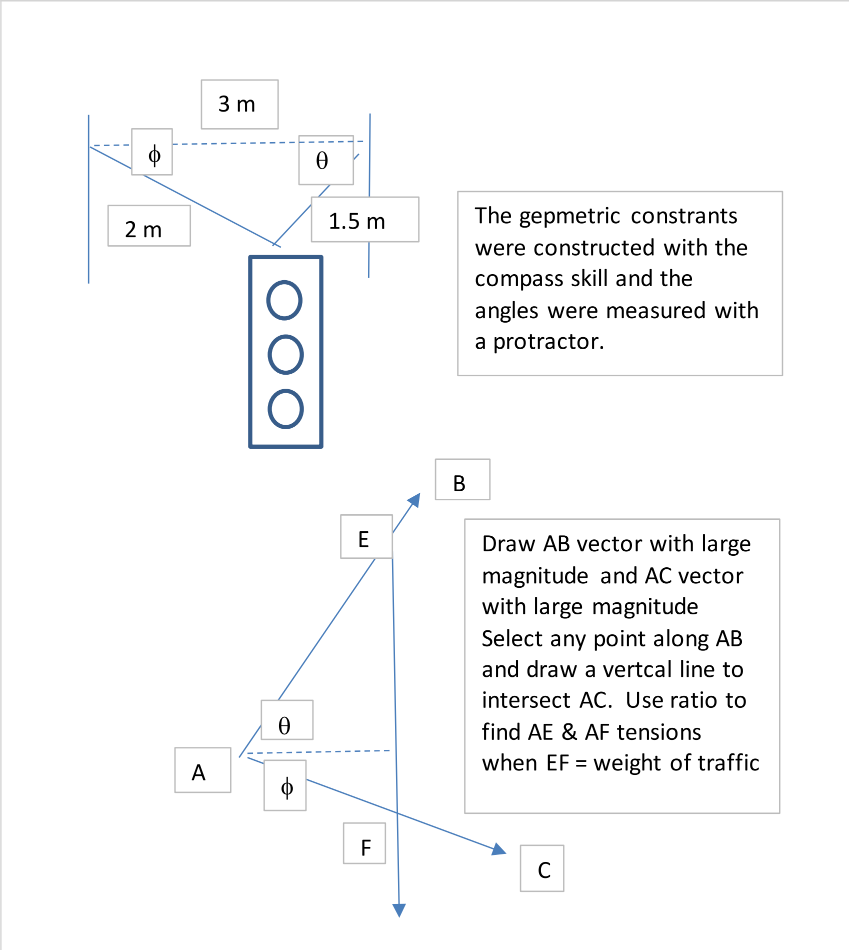


Figure 11. Relationships of vectors in the traffic light problem

The movable wedge problem delivered as illustrated in Figure 4 with a horizontal applied force was less successful in comparison. The used wedge mass was (10 + X/20) kg. There were 5 students getting the wedge acceleration within an uncertainty of 20 percent while the others lacked the cognitive stamina to complete the graphics of BF length versus mass ratio shown in Figure 5. Note that a 1-dim elastic collision problem of 3 kg and 5 kg masses resulted in a better learning outcome with 14 students completing the graphing task of finding the intersection pint of v1 final versus v2 final. The intersection of the energy equation curve (0.5*3*v1*v1+ 0.5*5*v2*v2 = energy constant) and the momentum equation linear line (3*v1 + 5*v2 = momentum constant) did not seem to overload their cognitive stamina.

The 2-car collision was used to reinforce the impulse-pair concept with one of the vector direction similar to the normal force direction in the movable wedge problem, shown in Figure 11. When the total energy was larger after the collision due to the large impulse pair, the questioning should be reversed such that students were asked to construct the initial momentum vectors, given the final momentum vectors, although the time reversal symmetry between the initial state and final state was not covered explicitly in our Principles of Physics class without algebra pre-requisite. The mass of car-a used in the assessment was (100 + X) kg with a small impulse, illustrated in the upper diagram of Figure 12. For the class of 18 students discussed above, 10 students were able to complete the assessment task.

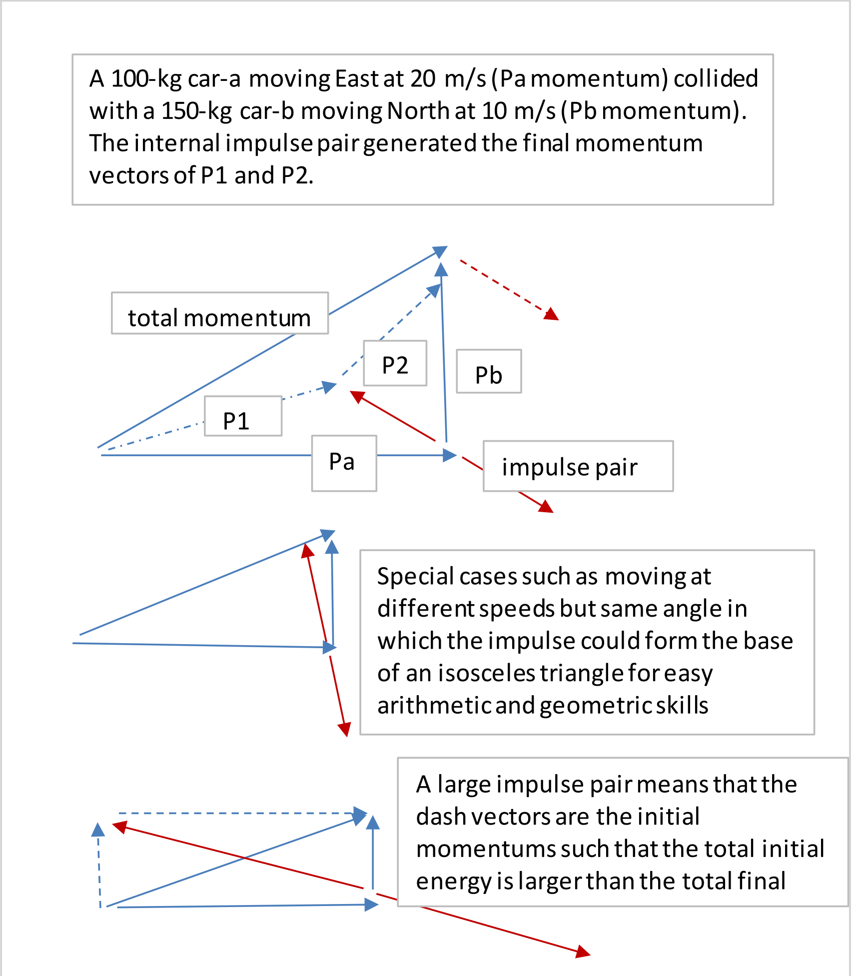


Figure 12. Relationships of vectors in the 2-car collision problem

The tested students in our community college setting did not have any inclination towards STEM majors because they were Business and Elementary Education majors. It is a working hypothesis that the presented spatial numeric method would work well in the Physics First Pedagogy in high school with open minded students interested in STEM majors. The 2007 Pedagogy Study published in Science criticized the Physics First pedagogy as having no bearing to the subsequent grades in Biology and Chemistry classes in the studied high school student population, but praised the high-school math grades as important (Sadler et al. 2007). Recent reports also cited math grades as a major factor in the transfer of math knowledge to the learning of university physics (Nakakoji et al. 2020), and in the equalization of wages in this era of growing inequalities (Black et al. 2021). The spatial numeric method presented in this article will enrich a math application experience, let alone in a Physics First pedagogy using protractor/ruler and arithmetic ratio skills. The spatial-numeric method is also helpful in the "Introduction to Research" course and "Use of Scientific Computer" course offered by our Physics Department. The set-theoretic classification of genes can start with graphs (Okano et al. 2023), while the geometric method pedagogy in the Van Hiele learning model has been studied (Pujawan 2020; Naufal et al 2012; Chen 2016).

Last but not the least, the rise of ChatGPT favors the use of spatial-numeric questions since graphical processing still poses a challenge to the ChatGPT inputs. The Reopen after COVID has posted considerable difficulties, as Higher Education has been modeled on a "burning platform", like Nokia in 2011 standing on a burning platform, in reference to an oil platform explosion in the North Sea (Wingard 2022). The advocate of adjusting the faculty delivery at least once every year could be fulfilled with the use of the spatial-numeric pedagogy when the numeric inputs are tied to the numeric information in the students' university ID numbers.

Conclusion

The study of cause and effect in terms of the normal force in the movable wedge using the spatial numeric method is a valuable tool which is suitable for the delivery of the Physics First pedagogy, thus eliminating the criticism based on the subsequent Biology and Chemistry grades. The spatial numeric skill required in any STEM subfields such as molecular biology, organic chemistry, etc. will be delivered early in the high school curriculum as Physics First pedagogy across the globe.

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