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# Improving fluid intelligence critical thinking via spatial reasoning ability in community college pre- engineering physics classes

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# Improving fluid intelligence critical thinking via spatial reasoning ability in community college pre- engineering physics classes

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Abstract
Spatial reasoning ability has been assessed via vector diagram construction method with the practical objective of incorporating as much as possible the available numerical values in a given problem, after the algebra based problem solving method had been assessed as crystallized intelligence at a satisfactory level. The post-score in the spatial reasoning ability learning model and pre- score in the crystallized intelligence learning model have been studied via data correlation. An assessment model of problem solving ability improvement in terms of pre- score and post- score data was developed. The ability to solve a similar problem containing modified constraints in terms of spatial reasoning with sketching and construction has been assessed as an indicator of fluid intelligence. The application of fluid intelligence assessment as an effective tool to assure "not-teaching to the test" in flipped classroom pedagogy is proposed, with inputs from cognitive studies that Intelligence is one of the most heritable behavioral traits. The assessment result differences in technology versus calculus physics classes in community college pre- engineering curriculum are discussed.

## I. Introduction

The critical thinking building skill in the high school years is customarily being measured via the SAT scores in critical reading, math, and writing. A college professor would need to work with the incoming students for continued growth of their critical thinking skill. A recent complaint by a Stanford professor on the Edge.org blog and Huffington Post said "All the mathematical methods I learned in my university math degree became obsolete in my lifetime" [1, 2]. A professor with physics education research interest, Rhett Allain of Southeastern Louisiana University, advocated the use of numerical calculation in introductory physics instruction on March 4 2017 via social media [3]. A natural extension to include a flexible programming language, Python [4], has been demonstrated with examples which include the crashing of an asteroid into the Sun via a spaceship momentum transfer process [5, 6], three body collision problem [7], video game analysis [8], etc. These two proclamations are indicative of our fast evolving education paradigm with the information revolution challenge propelled by social media driven technology. In particular, the use of Python on physics problems would depend much on fluid intelligence when Python code modification methodology is used [4]. The importance of fluid intelligence building in college years has undeniably become a center stage of learning and critical thinking assessment models would be needed to meet the challenges of social media. For professors in Southeastern Louisiana University with the LIGO project for gravitational wave detection, one would guess that their physics department would have an objective to train students in fluid intelligence via Python learning. On the other hand our community college is part of CUNY; our mission would be to train our students to transfer to senior college engineering programs in City College, Stony Brook University, etc. The usual practice of asking 7th semester engineering students to take the FE exam in City College, Stony Brook (Princeton has a practice of "6th semester taking FE exam" [9]), etc. has always been stressful for our community college pre-engineering students when planning their transfers. Our students could use a practical blueprint on how to improve fluid intelligence learning other than via the Python coding modification platform. Over the years, we had found that practical issues such as drawing to scale and radian versus degree modes in the TI calculator setting are obstacles to some of our first semester physics students. To promote fluid intelligence learning, we have been developing spatial reasoning pedagogy and assessment in engineering physics and technology classes.

## II. Spatial reasoning pedagogy

The learning of spatial reasoning ability has been assessed via vector diagram construction method with the practical objective of incorporating as much as possible the available numerical values in a given problem, after the algebra based problem solving method had been assessed as crystallized intelligence at a satisfactory level. The kinematics examples would start with velocity vector changing direction under the influence of gravity in terms of cause and effect direct thinking and reverse thinking when the final velocity is given instead of the initial velocity (Figure 1). The ill-structured problem of giving the initial velocity direction without magnitude and final velocity direction without magnitude in cell phone camera shots as the projectile information has been given routinely to gauge the development of fluid intelligence when the elapsed time between the two camera shots is known. In such a case, the position of the (9.8 m/s/s * t) vertical vector needs to be moved sideways until it would fit into a triangle since the length of v0 and vf are not known. The velocity addition with a parallelogram construction in constant acceleration was devised for ball throwing using displacement as the objective (Figure 2). The use of algebra in the (v0 + vf) vectors in Figure 2 shows that the vertical (g*t) vector and the (2*d/t) vector would give 1/2 (gt) = 1/2 (2d/t)*factor so that t = sqrt (2d*factor/g) with g = 9.8 m/s/s. Such a solution obtained by mixing measurement and algebra is an important tool to demonstrate the practical nature of spatial reasoning. The relative velocity diagram construction in non-90-degree situations is yet another measure of fluid intelligence development (Figure 3). Finally the construction of an orbit in a variable acceleration situation would thoroughly accentuate the spatial reasoning pedagogy in kinematics learning (Figures 4 and 5). The special case of circular motion when all the (a*t) vectors are constant in magnitude would yield a circular quadrant with length 2*3.14*v/4, which is equal to a*t with t given by 2*3.14*radius/v. The equality would then become v-sq/radius = acceleration, the physical meaning of uniform circular motion. The spatial reasoning influence to algebra thinking could lead to the discussion of using Excel simulation to find the elliptical orbit and the Feynman construction of ellipse in his lost lecture [10, 11]. Last but not the least, force diagram in an ill-structured problem, similar to projectile motion ill-structured problem, has been deployed to keep up the spatial reasoning paradigm in the first few weeks in Physics I (Figure 6).

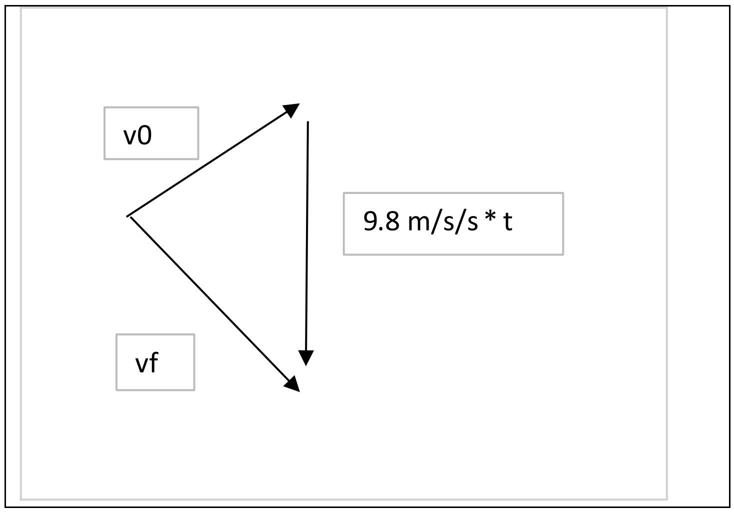


Figure 1: A diagrammatic representation of a projectile motion with v0 as initial velocity, vf as final velocity and (9.8 m/s/s * t) as the cause. When the magnitudes of v0 and vf are unknown, the fact that the (9.8 m/ds/s *t) vector must be vertical would yield an unique answer if the elapsed time t is known.

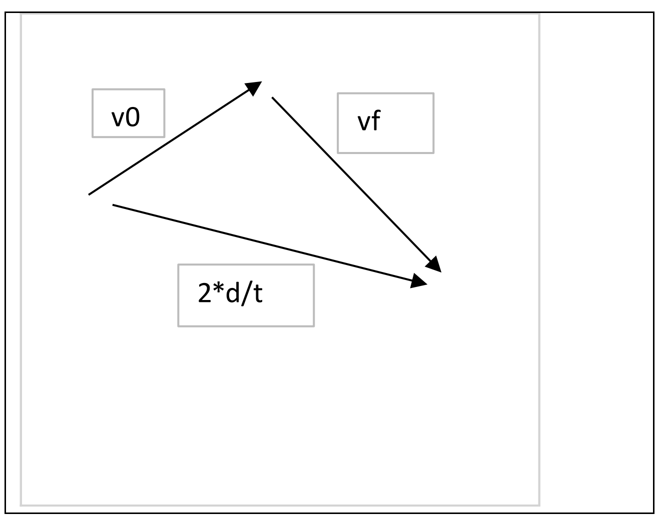


Figure 2: A diagrammatic representation of a projectile motion with v0 as initial velocity, vf as final velocity and (2*d/t) as the result with d being the displacement vector. Note that the vertical (9.8 m/s/s * t vector) would dissect the 2*d/t vector at its mid-point and they will form the diagonals of a parallelogram with v0 and vf as the sides.

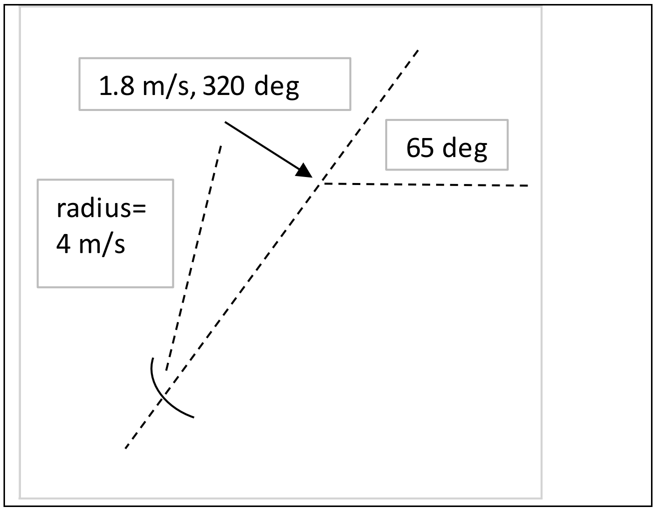


Figure 3: A diagrammatic representation of a relative velocity spatial reasoning example. A 4 m/s boat needed to go to a destination at 65 degree away with water current 1.8 m/s at 320 degrees. Spatial reasoning would require drawing the water current first. Then draw a line at 65 degrees at the end of the current vector, and then draw a circular arc (radius 4 m/s) with the current vector start point as a center using a compass.

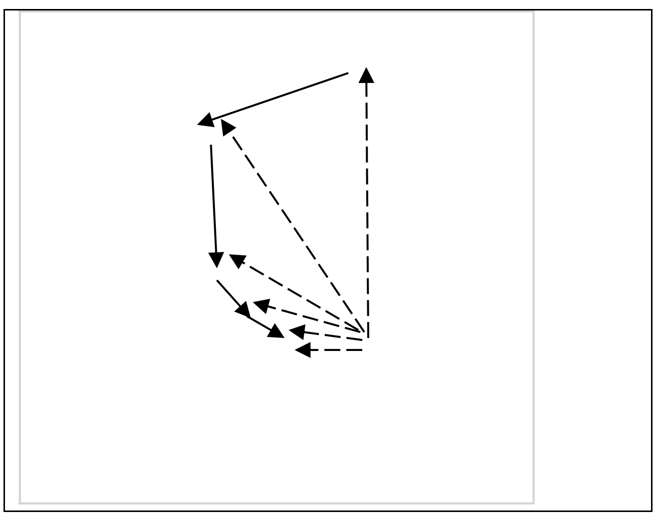

Figure 4: A diagrammatic representation of the orbital velocity changes. The dash arrows represent the velocity vectors. The vertical dash arrow represents the velocity at perihelion. The solid arrows represent the diminishing (acceleration *t) magnitude as the distances from a focus (with the massive planet/star) increases. The horizontal dash arrow would be the final velocity vector in this 4-segment approximation of the quadrant of an elliptical orbit, traced by a satellite going around Earth.

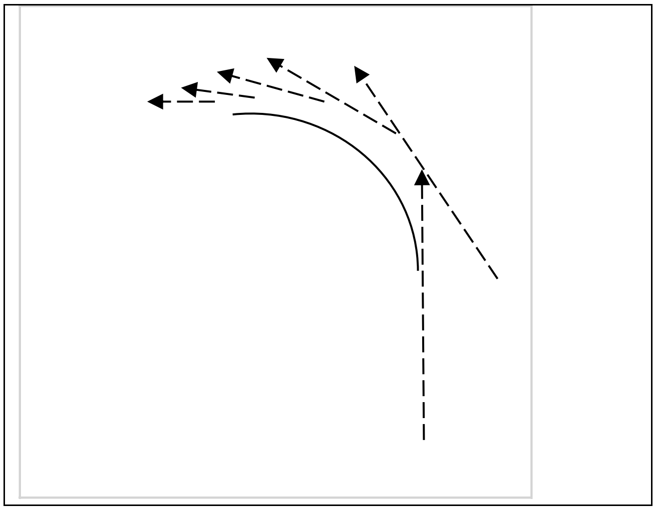

Figure 5: A diagrammatic sketch of the orbital velocity changes and an elliptical orbit. The dash arrows represent the velocity vectors. The solid curve would be the elliptical orbit in this 4-segment approximation of the quadrant of an elliptical orbit traced by a satellite going around Earth.

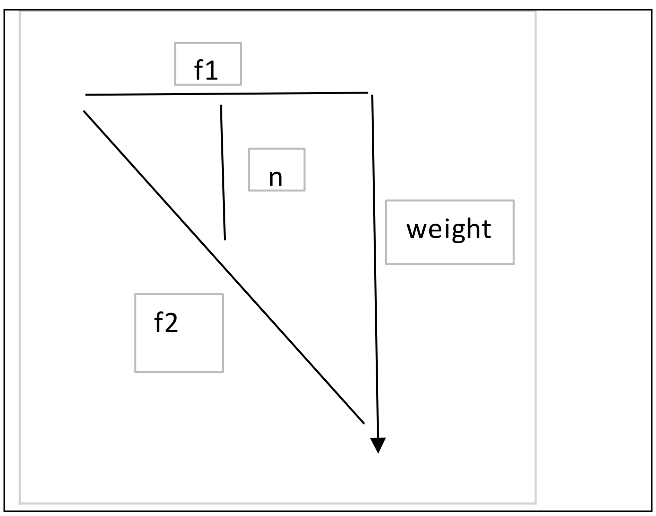


Figure 6: A diagrammatic representation of an ill-structured question involving forces. There are four forces, weight, floor normal contact force n, applied f-horizontal pointing to the right = f1, applied f-sideway at 150 degrees = f2. The drawing requires slightly higher spatial reasoning skill since there are uncertainly values on the magnitudes. A student could first draw the weight vector downward as illustrated by an arrow, then draw a line at 30 degrees off the vertical to the left at the weight-end and draw a line at 90 degrees protruding leftward at the weight-start. When f1 meets f2 then n =0. Therefore the question has many (f1, f2, n) sets, a flexible polygon drawing based on the ill-design philosophy.

## III. Assessment data processing and result

The ability to solve a similar problem containing modified constraints in terms of spatial reasoning using sketching and construction has been assessed as an indicator of fluid intelligence in this project. The post-score in the spatial reasoning ability learning model and pre-score in the crystallized intelligence algebra learning model were used as assessment data. A correlation graph with post-score as the y-axis and first-score (or pre-score) as the x-axis could demonstrate a growth as a result of the spatial reasoning pedagogy. The ratio of post-score / pre-score is related to the relative growth by a subtraction of 1. In other words, the slope of the post-score versus pre-score minus one would be a measure of the relative growth using the (post- pre)/pre concept.

The learning assessment rubric of Highly Competent, Competent, and Needs Improvement versus Participant Deliverables was used. The student relative growth was about 0.3 (N = 20 and N = 16, two classes) in the assessment model using highly competent =1, competent = 0.8 and needs improvement = 0.6). The rubric guideline is displayed in Table 1.

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| Participant Deliverable | Highly Competent | Competent | Needs Improvement |
|---|---|---|---|
| Spatial reasoning and sketching (20%) | Provided a clear and correct sketch. | Provided a correct sketch with one or two blurred linings. | Poor sketch with 3 or more blurred lines. |
| Spatial reasoning with drawing to scale (20%) | Provided a clear drawing in the correct scale with no mistake. | Provided a drawing in the correct scale but with one silly oversight-mistake. | Provided a drawing with the wrong scale. |
| Spatial reasoning problem with modified constraints (20%) | Provided a clear scaled drawing consistent with the modified constraints. | Provided a scaled drawing indicative of the modified constraints with one minor mistake. | Provided a wrong drawing inconsistent with the modified constraints. |
| Spatial reasoning problem with ill-structured (20%) | Provided a clear scaled drawing consistent with the ill-structured and found the answer by a measurement. | Provided a clear scaled drawing consistent with the ill-structured but found a partial answer. | Provided a wrong drawing. |
| Spatial reasoning mixed with algebra usage (20%) | Provided a clear scaled drawing and got the answer using measurement and algebra. | Provided a clear scaled drawing and got partial answer. | Provided a wrong drawing. |

Table 1: Spatial reasoning assessment rubric. The participants are students. Scoring could be performed when assigning Highly Competent = 1, Competent = 0.8 and Needs Improvement = 0.6.

## IV. Discussion

The spatial reasoning learning as an indicator of fluid intelligence critical thinking assessment result yielded about a 30% relative growth in our assessment data. Although the working rubric in Table 1 may not be of the best design, the growth would be expected to be higher than 30% with more home practice and in-class contact hours. A practical assessment of rote learning crystallized intelligence is possible using the assumption that low crystallized intelligence score together with low spatial reasoning score would be indicative of rote learning with minimal fluid intelligence development. The ad hoc intelligence growth concept has been used to assess learning-growth. Our low value of 30% could suggest a cognitive threshold for the transition from algebra crystallized intelligence to fluid intelligence. Simple physics quiz with slightly modified algebra steps usually would result in a high median score, but more involved modified algebra steps, similar to those in the Python modification examples discussed earlier, would generate a lower median score. The incorporation of spatial reasoning would serve as an additional tool for the assessment of fluid intelligence with relationship to algebra crystallized intelligence in a learning-growth model using intelligence growth concept. In fact a nonlinear association in terms of correlation and its statistics could be revealed in future studies, perhaps with neuroscience input for the hypothesis formulation. In any event, the dopamine dump association with the success in algebra crystallized intelligence learning was evident from the excitement during class discussion on the scores earned in a quiz [12]. It has been reported that an emotional brain would enhance learning [13], and the application of algebra crystalized intelligence to enhance fluid intelligence development would provide instructor a practical tool to assert that there is “no teaching to the test” in flipped class style instruction. When a student sees that the fluid intelligence learning is being built as an extension of spatial reasoning from simple algebra crystallized intelligence that he/she already mastered, the satisfaction measure would increase together with learning measure from earning scores in the spatial reasoning extension. UPenn researchers recently discussed brain remodeling that includes reasoning, coordination, decision making, motivation, and regulation of emotions; in a cohort of 934 youths ages 8-22 [14, 15]. Although brain maturity is still an open question in neuron based studies and emotion regulation has an association with mindfulness or linguistic signature [16, 17, 18], an experienced instructor would know that dopamine dump associated in learning must be regulated to prevent a learning measure from becoming a satisfaction measure entirely. A student usually understands that muscle building exercises carry the phrase “No pain no gain” in a gym setting. The extension of such pain-gain association to cognitive skill building in a classroom setting would raise the question of “How to measure the pain/discomfort in learning and how would a seasoned instructor gauge a lesson to achieve a balance between satisfaction measure and learning measure?”

The concept of self- assessment is a practical method for dopamine generation in the learning process of standard examples in physics. An assessment of rote learning with fluid intelligence growth could include the use of spatial reasoning to drive algebra equations. The open book/material quiz format has been used to ensure zero stress on memory when recalling the algebra crystalline intelligence steps. A simple example would be a rough-surface ramp problem where a block is being pulled up via a pulley connected to a vertically hanging block. The free body diagram on forces for the ramp block with Weight would have Tension arrow longer in length than the Weight*sin35 component and the corresponding algebra equation would have

Tension as the leading term ready to be decreased by friction and Weight*sin35. After the simple algebra steps of solving for the tension and the acceleration when the ramp angle, friction coefficient, and block mass values are given, a new situation where the vertically hanging mass is unknown could be given such that the acceleration is down the ramp at 0.1 m/s/s magnitude. The free body diagram would be modified such that the Weight*sin35 component is longer in length than the Tension, and the friction would flip direction when compared to the previous case of being pulled up the ramp. The corresponding modification on the algebra equations would be driven by the spatial diagram where W*sin35 become the leading term in the equation for the ramp block. About 30% of our community college pre- engineering students would forget to refer back to the spatial diagram but just would flip the terms in the algebra equation which then would give the wrong answer. Flipping the sign of acceleration would reflect rote learning of the ramp problem algebra equation in its math form but not its physics essence, and would suggest a minimal understanding of spatial reasoning in an open book/material quiz. Such an assessment of crystallized intelligence in solving the ramp problem would rely much on the spatial reasoning of the free body diagram with various sketched vector lengths. It is interesting to note that the decision of taking a short cut and bypassing the free body diagram reasoning could be related more to default behaviors (and the absence of executive control) than with emotion; as shown by a recent decision science report in which the conclusion of "The enemy of reasoning is not emotion, but a lack of mental effort" was supported by MRI data [19].

The other way of teaching directly the ramp problem cases (up the ramp, down the ramp, stationary with friction) could become rote learning for a student and an instructor would miss out on the opportunity of showing the students about self- assessment and fluid intelligence learning through spatial reasoning. Even with neuroscience finding on cognitive studies that Intelligence is one of the most heritable behavioral traits, the anchor on algebra crystalized intelligence would provide a solid platform to build spatial reasoning regardless of race/ethnicity, a crucial factor in the pre-college SAT critical reading score result [20, 21]. The recent advances in genetic neuroscience studies, including the identification of a fluid intelligence gene PRRC1 (Gene ID: 133619) and over 100 memory genes based on RNA expression and intracranial EEG data [22, 23], should not impose deterrents in designing lessons on fluid intelligence improvement for every student. Recently Mayo Clinic explained that epigenetics studies had shown that two cells with the identical DNA sequence will show different RNA expression data [24]. Together with a reported genetic correlation of 0.62 between intelligence in childhood and in old age [25], we propose that the spatial reasoning pedagogy should include a fluid intelligence component in a community college setting even with a low graduation rate of less than 50%. Whether fluid intelligence is a composite of several underlying specific cognitive abilities, a question raised by The National Academies of Science Engineering Medicine in 2015 [26], could be explored with spatial reasoning pedagogy and assessment. The use of brain stimulation based on causation revealed by EEG oscillation for cognitive process improvement was reviewed recently [27]. Last week McGill University reported that transcranial magnetic stimulation (TMS) in synchronization with the brain theta wave frequency improved working memory in a cohort of 17 individuals [28]. It would not be unexpected when commercial brain stimulation in synchronization with theta wave becomes available in the next decade. The effect of brain stimulation on spatial reasoning will become an important question.

The assessment result differences in technology versus calculus physics classes in community college pre- engineering curriculum have been observed. Technology students can master simple procedural rule learning and improve some crystallized intelligence readily, while some engineering students are complacent on simple procedural rule learning and make silly mistakes. The engineering students are better in spatial reasoning learning, consistent with their exposure to more abstract thinking like that in calculus once their curiosity is engaged, facilitated by rocket science like elliptical orbit and Elon Musk SpaceX visions and missions. There have been about 15% technology students that would continue to take calculus physics. Last year there were about 10% engineering physics students persuaded (or saved) from transferring out of pre- engineering, and we have attributed the building of confidence in fluid intelligence as a retention reason. A future study on whether improving writing would help fluid intelligence building is an interesting project, consistent with a Forbes article saying that "Contrary to myth, science is not a rigid and objective realm where "soft skills" play no role, but an intensely collaborative process where teamwork and communication are absolutely essential" [29].

## V. Conclusions

We have reported our spatial reasoning strategy for fluid intelligence improvement.
An assessment rubric was put forward for quantitative analysis with statistics to measure the growth of fluid intelligence, with a base reference of algebra crystallized intelligence. Future studies could include an examination of the effect of the liberal arts fluid intelligence on spatial reasoning fluid intelligence building.

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