THE EFFECT OF INSTRUCTION OF VISUAL/SPATIAL THINKING SKILLS ON LEARNING PHYSICS CONCEPTS

by

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May 2012

DEDICATION

To my parents Star and Bill, both dedicated public school teachers, who encouraged me to explore and discover new things on my own. For my supportive co-workers at Robinson Secondary School, especially Melissa Booker who shared her expertise and wealth of diagnostic materials. For Tess Diffenbaugh, my lab assistant who cut out the materials for the treatment and tallied countless piles of data. For my sons, Dan and Bill, who helped me keep my sense of humor even when I was grading labs. Mostly for my loving husband Dan who supported me in every way, every day since the moment we fell in love. Thank you all for encouraging and supporting me.

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ABSTRACT

Students with weak visual/spatial thinking skills often perform poorly in mathematics and science. The high school juniors I teach who had low scores on a test of visual/spatial ability also had low scores on their physics assessments. The treatment in this action research project was to provide instruction in visual/spatial thinking by using a tangible object (in particular cardboard vectors) that the student could manipulate at first then guide the students to use their "mind's eye" to manipulate the images without the manipulatives. A large majority of the students have shown significant improvement in both their visual/spatial skills and their understanding of basic physics.

INTRODUCTION AND BACKGROUND

Introduction

In 1958 as part of the great space race with the Soviet Union, the National Defense Education Act was passed in an effort to emphasize mathematics and physical science education. Today as we turn to science, technology, engineering and mathematics (STEM) for answers to many of our global challenges, STEM educators bear the responsibility of preparing their students to solve the problems of tomorrow. The methods that teachers use to educate our future problem-solvers have evolved since the great space race of the 1950's and 1960's. The instructional methods of those days have often been described as "stand and deliver" and focused on the transmission of knowledge primarily through lecture. The trend for instruction now is focused on the students, taking into account their strengths and, in the case of this study, their weaknesses.

Background

"*Why do students who struggle to understand physics content routinely choose purely verbal activities over activities that have both a verbal and a visual component?"* This was what I wondered one day during a background vocabulary lesson in which students could choose between two similar activities. "*Is there a relationship between these students' visual/spatial abilities and their ability to succeed in physics?*" When the pattern appeared in all four of my physics classes last year, I decided that I had something worthy of study and I wondered if I could give these students some instruction on visual/spatial thinking in hopes that it would improve their abilities to grasp physics concepts.

What is visual/spatial thinking? According to Alan McCormack, past president of National Science Teachers Association, “Visual/spatial thinking (VST) involves directed use of the “mind’s eye” to develop mental pictures or images…to solve problems, create new ideas, and improve physical skills”(McCormack, 2011, p.10). The taxonomy of VST skills according to PROJECT VISTA (McCormack & Mason, 2000) includes some of the components in the following table. Only the skills that pertain to the physics classroom are in the table below.

Table 1

Taxonomy of Visual/Spatial Thinking Skills (Adapted from McCormack & Mason, 2000)

Visual/Spatial Perception	Visual/Spatial Memory	Logical Visual/Spatial Thinking
Ability to form mental images of observed objects Ability to observe fine details of objects Making connections between real objects and drawings, photographs, or media images that represent the objects	Storage and retrieval of mental images representing observed objects Communicating descriptions of previously perceived objects through drawing Visualizing objects based on verbal descriptions	Visualization of elements in a pattern Visualizing objects as observed from different points of view Interpreting 2-D representations of 3-D objects Visualizing motion of objects

When I considered these details of visual/spatial thinking in terms of the skills my physics students needed in order to master the physics content, I realized that strengthening these VST skills could possibly help students who historically struggle with physics. Some physics students cannot accurately represent, analyze or decode visual representations of physics concepts such as motion maps, graphs, vectors, free-body diagrams, fields, cycles and circuits. See Figure 1 below for examples these physics concepts.

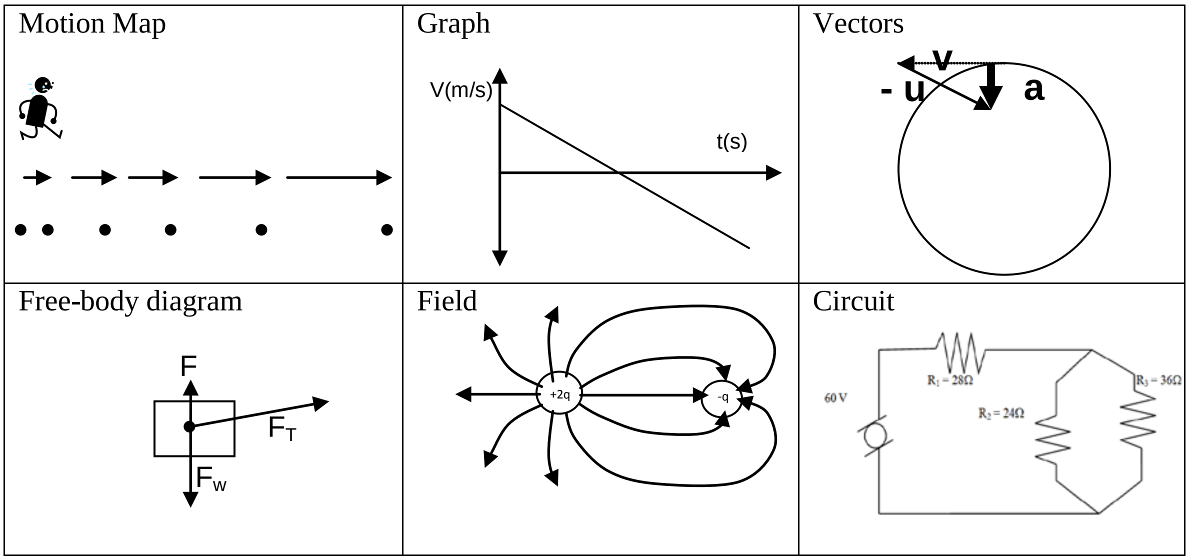


Figure 1. Examples of the Visual Representations in Physics.

I hoped that instruction in VST skills could strengthen my students' visual/spatial thinking so that the students' understanding of the physics content would improve along with their grades and possibly their attitudes about the course. The challenge was for me to determine *how* to strengthen my students' visual/spatial thinking skills. My first step was the development of research questions. My primary research question was:

I: What is the effect of instruction in visual/spatial thinking skills on the learning of physics concepts?

When considering the research in its entirety, secondary questions arose such as:

II. What is the effect of instruction in visual/spatial thinking skills on students' visual/spatial abilities?

III: What is the effect of instruction in visual/spatial thinking skills on students' attitudes about the physics course?

IV. What is the effect of instruction in visual/spatial thinking skills on the instructor?

Next, I solicited three people to support me during my action research: my husband who read my written work for clarity from the perspective of someone who is relatively unfamiliar with the topic (at least he was when I started); one of the other physics teachers at my school who teaches the same demographic group that I do; and my lab assistant at the time who was a former student of mine and was willing to give me her honest feedback on surveys and questionnaires that I used with my students. I solicited their feedback on my new research after I explored prior research by others who had investigated topics similar to mine.

CONCEPTUAL FRAMEWORK

In 1966 developmental psychologist Jean Piaget was one of the first to recognize the importance of visual/spatial thinking and imagery when he studied children's drawings (Piaget as cited in Ramadas, 2009, p.302). More recently Allan Paivio's (1995) dual coding theory and experimentation indicate that we process imagery faster than we process verbal cues. This theory is utilized effectively when mathematics teachers employ various *manipulatives* during math lessons, but the use of instruction of visual/spatial thinking and imagery is still under-utilized in physics education.

In a study examining the use of visual/spatial thinking in the science classroom one researcher described the approach as being overlooked. “School education tends to emphasize verbal and algebraic thinking, at the expense of visual and spatial modes” (Ramadas, 2009, p. 302). This is potentially a serious weakness on the part of science educators. There is overwhelming historical evidence of the significant role that imagery and visual/spatial thinking has played in the development of many scientific theories and breakthroughs: Faraday’s visualization of “lines of force” around charged objects; Tesla’s ability to visualize an entire working model in his mind; Einstein’s “thought experiments” dealing with special and general relativity; Friedrich Kekulé’s cyclical benzene; Newton’s expansion of the trajectory of a projectile to orbital motion; and Feynman’s diagrams for quantum field theory (Mathewson, 1998, p. 37; Ramadas, 2009, p. 308). All of these were vivid images that led to new scientific discoveries.

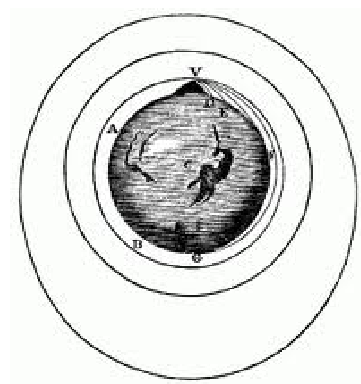


Figure 2. Newton’s Orbiting Projectile.

In my own classroom an informal analysis of my students’ visual/spatial skills led me to consider the link between this research and my students’ abilities to fully grasp physics concepts. At the start of every new physics unit I offer students a choice between two different background vocabulary activities. When offering my students the choice between a purely verbal activity and one that was both verbal and visual, the students with the lower summative assessment scores *always* chose the purely verbal activity. I suspected that these students were not comfortable using visual stimuli whereas their counterparts, who were also more successful in learning physics, were using visual stimuli and verbal cues. I wondered if I could help the weaker physics students by improving their visual/spatial thinking skills. I started by looking for evidence that visual spatial thinking skills could be learned AND that, once learned, there was benefit to learning physics concepts.

In a study of the effect of sensory cues on physics learning, Miriam Reiner (2009) explored the visual representations that students created to represent the physics concepts surrounding magnetic phenomena such as the forces and fields magnets create as well as their affect on the motion of a ferrous pendulum. The students were exposed to a pendulum affected by a magnetic field at a museum. Next they used their visual/spatial memory to "communicate descriptions of previously perceived objects through drawing" (McCormack, 2000, p. 11). Their communication was in the form of drawings that required them to "use creative visual/spatial thinking to imagine the explanation or the operation of the physical system" (McCormack, 2000, p. 11). Reiner, like other theoretical researchers (Mathewson, 1998; Ramadas, 2009; Vygotsky, 2008), postulated a cyclic nature to the acquisition of new knowledge during which one's mind rotates through what we remember, often stored as imagery, in comparison to the new perception to construct new meaning; *to learn*. Reiner discovered that there was indeed a visual component to learning the physics of magnetic interactions.

Additional studies have established longitudinal evidence that visual/spatial abilities respond to instruction and mediation (Potter et al., 2008; Piburn et al., 2005). In a twenty-year study of engineering students (*N*=1531) to improve student performance in engineering graphics the researchers first established that visual spatial ability was the strongest indicator of success in engineering graphics courses. Next they implemented "high imagery instruction" that improved their overall pass rate from 68% to 77% with the greatest gains for those receiving the additional instruction; their pass rate for one sub-group went from 20% to 80% (Potter et al., 2008, p.119). In another study researchers explored the role of visualization on learning geology. They created an intervention that consisted of practice with "pattern detection, ordering, rotation, and mental manipulation of three-dimensional objects" (Piburn et al., 2005, p.518). Approximately half of their students self-selected to be in the intervention group. These students had a mean normalized gain of 60% compared to a mean normalized gain of 45% for the control group of students who did not experience the intervention. They found that their intervention completely closed the observed achievement gap for their geology students ($N \approx 100$) (Piburn et al., 2005, p.519).

Given the previously mentioned evidence, one wonders why instruction in visual/spatial thinking isn't widely used in all high school physics classrooms. I conclude that possible reasons include: 1) The recently popular multiple intelligence idea focuses more on identifying the various strengths and learning styles that students have rather than *seeking to strengthen* their areas of weakness. 2) Not all high school students are fully advanced to the Piagetan level of cognitive development that is characteristic of visual/spatial thinking. 3) Visual/Spatial materials that correlate directly to physics curriculum are extremely rare. Regardless of the reasons it is not currently being done, the benefit of training students in visual/spatial thinking could be huge. With proper instruction, physics students should be better able to: draw and interpret graphs and motion maps; draw and interpret free-body diagrams; visualize the abstract (fields) and the microscopic (electrons); and problem-solve in physics.

Imagery and visual/spatial thinking skills are valuable to learning many different sciences. Helping students strengthen these skills would likely improve their understanding of the science content.

METHODOLOGY

The treatment I implemented was an attempt to strengthen my students' visual/spatial thinking skills. I decided to borrow an approach from mathematics teachers who use manipulatives; we used cardboard vectors (arrows that indicate the size and direction of a physical quantity such as force, velocity, displacement, acceleration or momentum). My plan was to use the manipulatives at first to help the students build their concrete understanding of a concept then wean the students from the manipulative so they would use their mind's eye to do the manipulation without the physical manipulatives. Before the treatment began, however, I collected diagnostic data.

The first diagnostic assessment was the Spatial Ability Test (Newton & Bristol, 2009) which allowed me to identify which of my seventy-six International Baccalaureate Physics-1 students might benefit most from my treatment. I identified a group of sixteen students in the lowest quartile then after successive assessments such as homework, formative assessments and summative assessments, nine of the original seventeen stood out as the students who were the focus of my treatment because they struggled the most. It was this group of students who I hoped would benefit the most from the treatment.

(The research methodology for this project received an exemption by Montana State University's Institutional Review Board and compliance for working with human subjects was maintained.)

The physics quantities that are always the newest to physics students (and have the most visual aspect) are vectors. Before I began any instruction in vectors I administered a Vector Diagnostic (Nguyen, & Metzer, 2003, pp. 630-638); the average for all of my students was 70% with 12 of the 17 students with weak visual/spatial skills scoring below the class average. One of the first things we did with the vectors was to see and measure the result of adding them together tip-to-tail. It is counter-intuitive to some students that a displacement vector of 6 meters (blue) could be added to displacement vector of 8 meters (gold) and yield an answer, called the resultant, R (black), that could have *any* value between zero and 14 meters. See Figure 3 below.

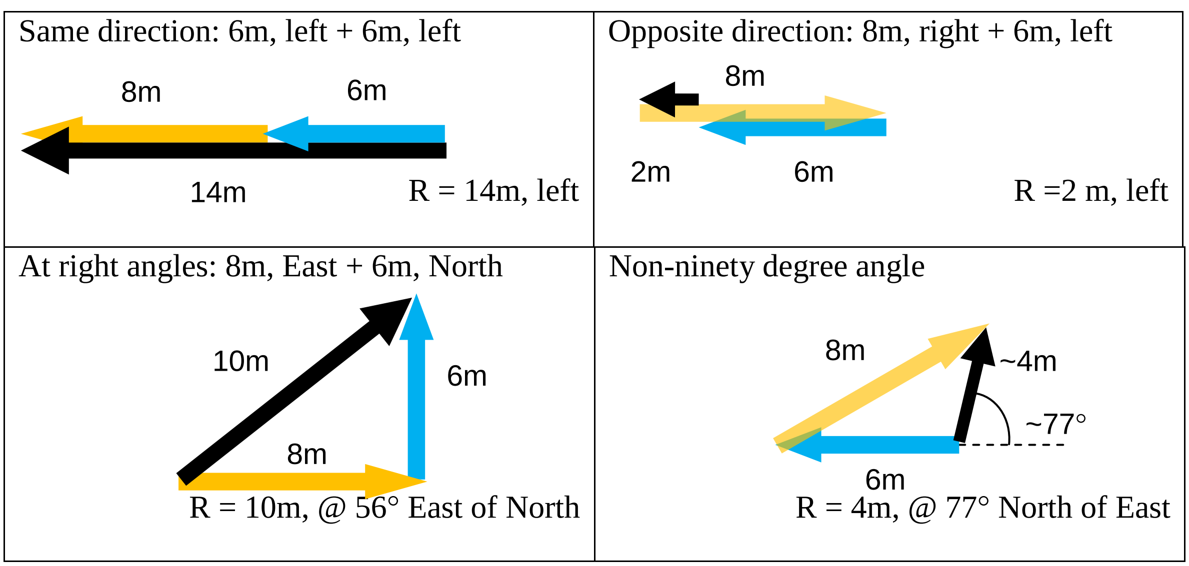


Figure 3. Samples of Vector Addition.

Another use of the vector manipulatives was in the unit on forces. Historically a challenging skill for the students to learn has been the creation of a net force diagram (force vectors added tip-to-tail) from a free-body diagram where the forces that are acting on an object are all drawn tail-to-tail emanating from the object's center of mass. (See Figure 4 below.) In the lab for this topic the students suspended an object of unknown weight in static equilibrium from two force measuring spring scales as shown in the left box of the figure.

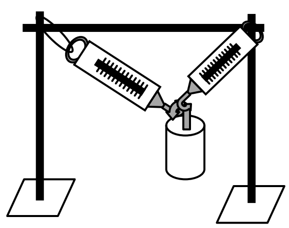
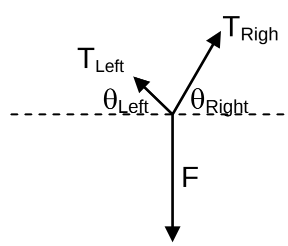
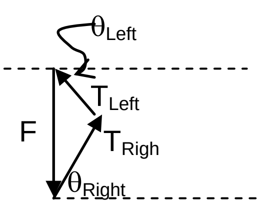
Lab set-up of an object in static equilibrium	Free-body diagram of an object in static equilibrium	Net force diagram of an object in static equilibrium
		

Figure 4. Development of the Net Force Diagrams.

The students recorded the values of the springs' tension forces and their angles in diagrams similar to the center box of the figure. In the last step the students had to rearrange the three vectors to create scale drawings of the net force (resultant). In past years the last step was a source of frustration for the students that resulted in very little success. I would estimate that in past years nearly half of my students did poorly on this part of the lab. This year the students used their cardboard vectors to make the transition from free-body diagram to net force diagram (box on right) with 100% success.

Treatment

For six months, during each of the nine units of study that included vectors (kinematics, forces, freefall, projectile motion, momentum, uniform circular motion, gravitation, momentum and electrostatics) I modeled vector addition, vector subtraction and vector components with the aid of the cardboard vectors. I also provided each student with a set of twelve cardboard vectors measuring 2 cm wide and having lengths of 5, 6, 8, 10, 12, 13, 16, 18, 20, 25, 27 & 30 cm for in-class use. Since most of our work with vectors involved right-triangle trigonometry, I also provided each student with dry erase markers and a laminated piece of graph paper for both facilitating the orientation of the cardboard vectors at right angles when necessary, and for the part of the treatment when we transitioned away from using the manipulatives to drawing the vectors. The use of the vectors during any given lesson was similar to what most physics teachers draw for their students when analyzing vectors, but presented with the tangible cardboard vectors. The unique part was that the students could see the vector being moved from one location to another, to do a vector addition for example, while its length was obviously not changing and its orientation (the heading or angle) could be maintained with use of the graph paper. An example of a vector addition is seen in Figure 4: Development of Net Force Diagrams on page 10. Early in the treatment, when the students worked through vector exercises, I noticed that on average three out of every four of my students used the cardboard vector manipulatives. As the year progressed fewer and fewer of the students elected to use the cardboard vectors; most were able to successfully draw the vectors for an addition, subtraction or components. For a more specific account of my measurement of the treatment I'll describe my research design.

Research Design

To answer my research questions my plan was to use some well-established assessment instruments in order to help insure validity and reliability.

1. I administered a diagnostic assessment of my students' visual/ spatial abilities as both a pretest in September and a post-test in February. See the Spatial Ability Test in Appendix A.
2. I administered a diagnostic assessment of my students' understanding of force concepts as both a pretest in October and a post-test in February. See the Force Concept Inventory in Appendix B.
3. I administered a diagnostic assessment of my students' skills with vectors as a pretest in October did a post-test in January. See the Vector Diagnostic in Appendix C.

In addition to administering these assessment instruments:

4. I kept records of my students' work samples that assessed their understanding of physics concepts and their visual/spatial abilities.
5. I collected student feedback on their perceived understanding of the content as well as their attitudes about the course and the treatment through surveys, questionnaires and interviews.
6. I recorded my own observations about the treatment.

The research plan followed the schedule outlined in the Table 2 below.

Table 2
Data Collection Table

Dates	Physics unit of study	Data Collection Methodologies	Data Collection Instruments	Research question
9/6/2011 and 5/8/2012	Lab Skills	Diagnostic Test	Spatial Ability Practice Test	II. Visual/spatial abilities
9/26/11	Kinematics	Formative Assessment	Slopes and Areas homework	I. Physics Learning
10/8/11	Kinematics	Student Work Samples	Graph of accelerated motion in lab report	I. Physics Learning
10/7/11 & 10/16/11	Kinematics	Summative Assessment	Graphing and Kinematics Unit Test: first test and re-test	I. Physics Learning
10/12/11	Kinematics	Observation	Journal entries: Observe participants correcting tests	II. Visual/spatial abilities
10/11/11 & 1/4/12	Vectors	Diagnostic Test	Vector Pre-Test	I. Physics Learning & II. Visual/spatial abilities
10/16/11	Vectors	Formative Assessment	Formative assessment on vector magnitude and direction; adding vectors and vector components	I. Physics Learning & II. Visual/spatial abilities
10/17/11 2/9/12	Forces	Diagnostic Test	Force Concept Inventory Test	I. Physics Learning
11/2/11	Forces	Student work samples	The "Rock" lab- Unknown mass suspended from 2 spring scales	I. Physics Learning & II. Visual/spatial abilities
11/8/11	Forces	Formative Assessment	Formative Assessment on Equilibrium	I. Physics Learning
11/8/11	N/A	Survey	End-of-quarter-1 survey of attitudes	III. Students' attitudes
11/8/11	N/A	Interviews	Select participants from end-of-quarter -1survey for follow-up	III. Students' attitudes
1/11/12	N/A	Survey	Science Placement Survey- next year's science enrollment	IV. Second year enrollment
1/11/12	N/A	Interviews	Select participants from survey results	IV. Second year enrollment

I selected the first instrument, the Spatial Ability Practice Test (Newton, P. and Bristol, H., 2009), to evaluate each student's "ability to mentally manipulate shapes". The 45-question Spatial Ability test was administered to all 76 of my International Baccalaureate Physics-1 students. I selected this test because it tested the students' abilities to perform some of the most challenging visual/spatial manipulations used in physics. The first thirty questions required the students to match a geometric shape in one group with the same rotated geometric shape in a second group. This is a skill that physics students use when they are learning about inclined planes. They need to be able to see similar triangles in both the measurements of the inclined plane itself and the triangle formed by the weight vectors and its parallel and perpendicular components as seen in Figure 5.

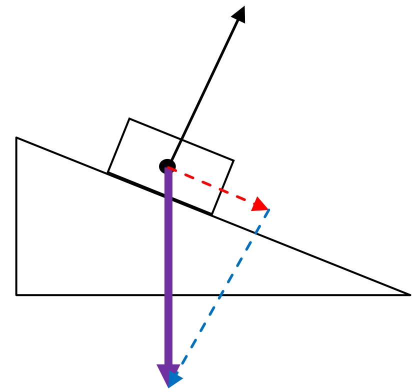


Figure 5. Inclined Plane.

Questions 31-36 show the assembled shape for tangram puzzles and require students to identify which tangram pieces could have been used to assemble the shape. In physics, students are required to evaluate areas on graphs due to their representing physical quantities. For example the area between the graphed function and the time axis on a velocity versus time graph represents the object's displacement. There are four more such quantities in the physics that I teach that are represented by areas on

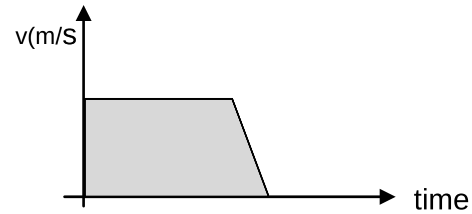


Figure 6. Graph of Area Representing Displacement.

graphs. I felt that the students' abilities to evaluate areas could be assessed with these questions.

Questions 36-42 assessed the students' abilities to use their mind's eye to manipulate a two-dimensional representation into a three-dimensional shape. In physics there are some concepts that have a three-dimensional nature that cannot be taught any other way. In magnetism when a conductor is moved perpendicular to a magnetic field there is an induced emf as indicated in Figure 7. The students must be able to visualize a three-dimensional relationship on a two dimensional page or screen.

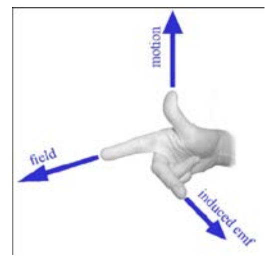


Figure 7. Right-hand Rule.

Finally, the last few questions on the Spatial Ability test were map reading questions. In physics the concepts of having a reference point and movement in various directions are major components of kinematics. Although the representations of the skills on the assessment are not identical to the way the skills are represented in physics class, we do need to use each of the skills assessed for different concepts in physics. I felt the test would definitely indicate which students had weak spatial abilities. As to the reliability of this test, during the previous school year I administered the test to my higher level senior physics students. These students were the most successful students in the first year course as juniors, they self-selected the second year of physics at the higher level and the majority of them planned to pursue engineering or physics as a college major. These students should have scored very high on the Spatial Ability Test; they did. In this select group (*N*=24) 83% of them scored above 90%. These students were in the top 10% of all students in my school.

For some demographic background of my students and my school: As the largest secondary school in the state of Virginia there are over 4000 students of which ~60% are White, ~20% are Asian, ~10% are Black and ~10% are Hispanic. Twelve percent of the student population is economically disadvantaged. The school offers both Advanced Placement courses and the International Baccalaureate Program. In 2012, U.S. News and World Report ranked my high school 88^{th} in the country and 5^{th} in the state of Virginia. With 90% of the students taking at least one IB or AP class they have a college readiness index of 76.3 (McMullen, 2012). In a class of approximately 700 students there are typically about180 juniors (25%) who, having completed an honors level biology course as freshmen and an honors level chemistry course as sophomores, elect to take IB physics-1; another 180 or so take non-IB physics while some students elect to wait until their senior year to take a physics course. Pre-Calculus with Trigonometry is a co-requisite of the IB physics-1 course, so the students have had exposure to some trigonometry from their previous math courses. (Physics students use trigonometric functions to perform quantitative analysis of their vectors.) The gender breakdown in the IB Physics-1 course is often 50% male and 50% female. Analysis of pre-test and post-test data of spatial abilities did not reveal any gender differences in the first year course; however the same cannot be said about the Force Concept Inventory results.

The authors of the diagnostic instrument called the Force Concept Inventory claim that, “The Inventory data provide a clear, detailed picture of the problem of commonsense misconceptions in introductory physics" (Hestenes, Wells, & Swackhamer, 1992, p. 142). I chose this instrument because historically it reveals the many misconceptions that students have about how the physical world works. Some misconceptions are so ingrained that even the post-test score average for master teachers' students can be as low as 50%. The test assesses some of the following misconceptions:

1) Two unequal masses falling side-by-side, accelerate differently.
2) When a large or fast object collides with a small or slow object the forces that they exert on each other differ in size.
3) A moving object "has a force".
4) An object that spins out of a circle, still moves in a curved path despite a lack of an inward force.
5) Acceleration is zero at the highest point of a projectile's trajectory.

Students who overcome misconceptions such as these can have more success in physics than their counterparts, who cling to their pre-Newtonian beliefs. In addition to mastering these concepts they need to have the skills to perform quantitative analysis as well. For that skill I administered the Vector Diagnostic (Nguyen, & Metzer, 2006).

The vector diagnostic instrument has questions that require students to: compare vectors' sizes and directions; add vectors; and draw conclusions about their resultants. The authors of the quiz administered it to over 2000 students in a college physics course at Iowa State in 2000-2001with surprisingly disappointing results. Although vector notation and instruction can differ greatly between math courses and science courses and from one textbook author to the next, the terminology and symbols used in the vector diagnostic are consistent with what is taught at our school among the physics instructors.

In addition to the assessment tools described above, I administered formative assessments during each unit to track my students' learning, specifically their progress in using their mind's eye instead of their manipulatives when needing to use visual/spatial thinking. When I first introduced vectors I administered a formative assessment that required the students to scale, draw and measure vectors as well as add them and calculate their resultant's magnitude and direction. See Appendix D. Later in the treatment I administered a formative assessment that required the students to draw a free-body diagram of an object in equilibrium to assess their progress in understanding forces as vectors. See Appendix E. For insight into how my students thought the treatment was affecting both their learning and their attitudes about the course, I asked them direct, open-ended questions on surveys and questionnaires at the end of each quarter such as, "*I have been trying to strengthen your visual/spatial thinking skills by using a lot of visual cues and manipulatives like the cardboard vectors. How has the use of these tools affected* ***your attitude*** *about the class?* Data and analysis from these instruments follows.

DATA AND ANALYSIS

Analysis of the data supports the conclusion that physics students' visual/spatial skills improved over the course of the treatment. While the students understanding of physics concepts would naturally improve in any physics class over the course of instruction, the amount of improvement for students in the treatment was somewhat greater than typical. The students' attitudes about the treatment were enthusiastic; they cheered and applauded, when I shared the following visual representation of their growth in visual spatial thinking seen below in Figure 8.

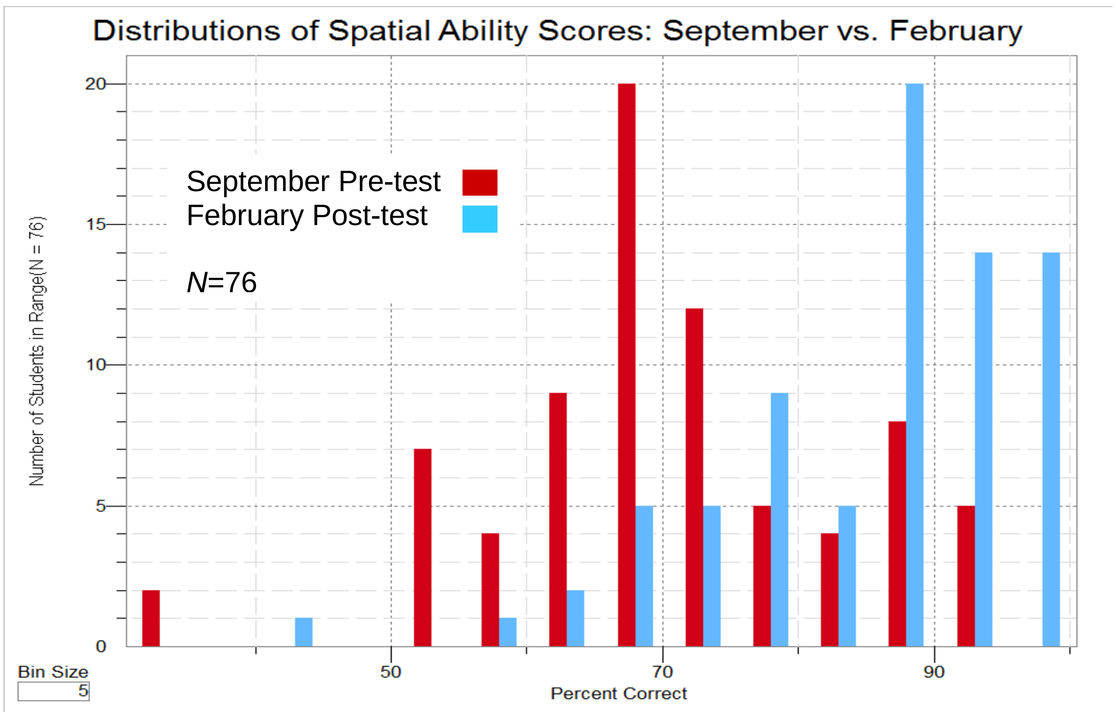


Figure 8. Distribution of Spatial Ability Scores Pre-test vs. Post-test.

The red pre-test bell curve data fit a normal distribution while the blue post-test data resulted in more of a mountain curve. The data statistics for the pre-test were (M = 70, SD=13) while the post-test results were (M= 85, SD = 11). The t-test conditions were t= 8.7×10^{-18}; one-tailed. Further analysis of the students' work and interviews with the students revealed some non-quantitative results. The students had 20 minutes to complete both the spatial ability pre-test and post-test. However 45% of the students left sections of the pre-test blank or admitted to guessing as time was running out. This was not the case for the post-test. Some students finished with as much as 5 minutes to spare while all but 4 of the 76 students were finished when the 20-minute period expired. When I interviewed the few students who finished early they told me that because they were familiar with the format of the test, they did not "waste time" reading the instructions as they had on the pre-test. Another student said that she remembered which type of questions she liked the most, finished those first, and then had sufficient time to spend on the ones that were more difficult for her. Finally, all but two of the 76 students had significant (mean of 50%) normalized gain (actual percent increase divided by potential percent increase). This means that the students' spatial abilities grew significantly from September to February. There was no difference in the normalized gain when comparing the bottom and top quartiles of students indicating that all of the students experienced improvement in their spatial abilities during the six month period. Similar analysis was performed on the Force Concept Inventory data.

According to the authors, the Force Concept Inventory test typically averages 20% correct on a pre-test and 50% correct on the post-test (even for students of master teachers). Those scores would indicate average normalized gains of just below 38% (30% gain ÷80% potential gain = 37.5%). My t-test analysis results were (M=26, SD=14) for the pre-test and (M=69, SD=16) for the post test with $t= 4.9 \times 10^{-35;}$ one-tailed. The visual representation of the data is below in Figure 9: Distribution of FCI Scores. The pre-test data (from September) is in red while the post-test data (from February) is in blue.

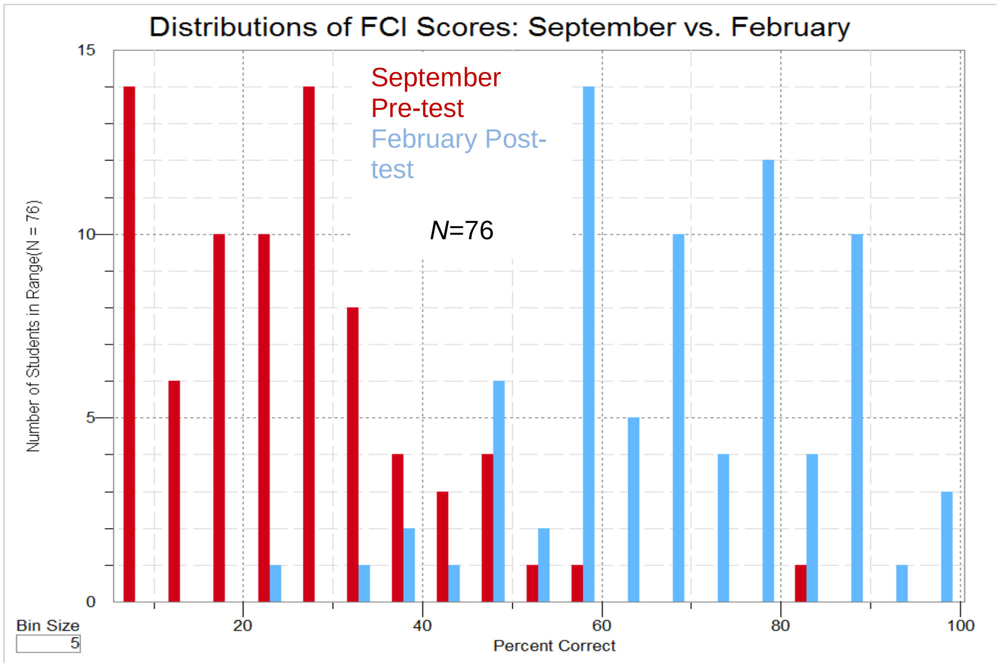


Figure 9. Distribution of FCI Scores.

Gender analysis of the FCI results indicated that the female population (*N*=25) started with a 10% gap in understanding at the time of the pre-test, experienced 9% less (53% compared to 62%) normalized gain than the male population (*N*=51) and that the males maintained the 10% lead on the FCI in February. An interview with one female student who struggled with her spatial abilities all year uncovered a difference in the type of play that girls and boys experience as youngsters. She recalled a childhood filled with books, reading and "academic" adventures while her male counterparts had more physical adventures at the playground on swings and the merry-go-round; the very experiences that help students understand forces on objects in motion. If this gender difference in childhood experiences are effective in the development of visual/spatial abilities, it explains why the top quartile of students in the post-test of the FCI is predominantly male with only 3 of the 19 students in that group being female. There is the possibility of gender bias in some of the questions, but the more likely cause is the type of play and activities that the children have experienced growing up like my student described. Although interesting, this is a topic for further study, beyond the intent of this research. Instead, I'll delve into deeper analysis of the specifics on the vector manipulatives. In the future, however, physics instructors might consider exposing their students to typical playground activities and more active learning in general.

After sixteen weeks of instruction and activities using the manipulatives such as have been described in the method section of this study, I administered a summative assessment and a survey on vectors. Analysis of my students' developing vector skills and their survey results follow.

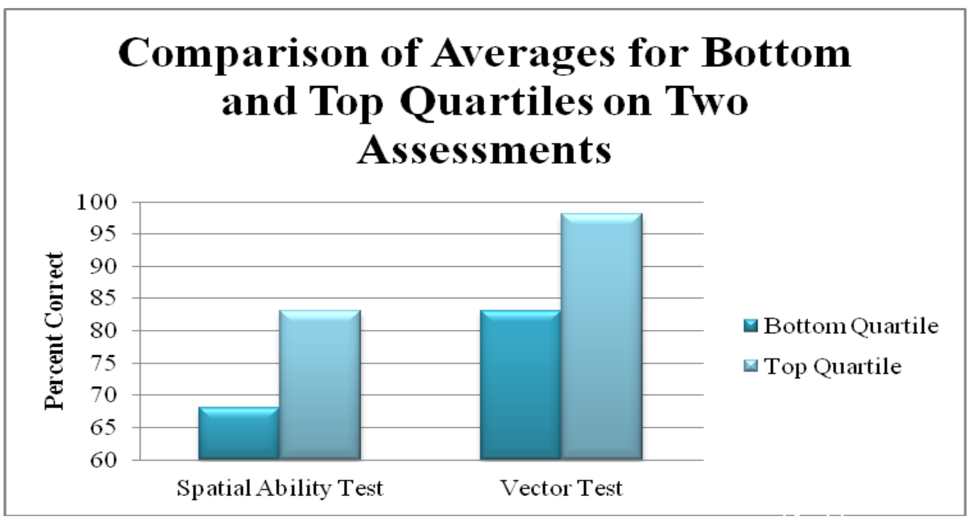


Figure 10. Comparison of Bottom and Top Quartiles on Two Vector Assessments, (*N*=38).

Figure 10 above supports my suspicion from last year that students with strong visual/spatial skills outperform their counterparts with weak visual/spatial skills on physics concepts, in this case vectors. The students with the strong visual/spatial skills and high achievement in physics reported having past-time activities that have a visual/spatial component to them for example: video games, puzzles and building blocks such as Legos. The students who scored on average fifteen percentage points higher than their peers on the diagnostic test (seen on the left) also scored on average fifteen percentage points higher than their counterparts on the summative vector test (seen on the right).

After the summative vector assessment I administered a brief (2-question), anonymous survey to ascertain how using the cardboard vectors affected the students' attitudes about the class. Of my 76 students, 88% responded that they felt "a little more positive" or "much more positive" about the class than if we didn't use them. The comments from these students included the ideas that "the tools helped solve the problems" and "they help to visulaize." Only 6% said that they felt "a little" or "much more negative" about the class because we use the cardboard vectors. In the small, negative group, the explaination for their responses contained the sentiment that the vectors were "silly" or "unnecessary." The 5% of students in the "other" group had responses such as: "no effect" and "I feel indifferent." The students in this "indifferent" group were already very high ahievers in physics. So, overall, using the cardboard vectors has had a positve effect on the majority of my students' attitudes about the class.

Before the treatment began most of my students had no exposure to the concept of vectors and what they thought they knew about vectors was riddled with misconceptions. Analysis of the Vector Diagnostic instrument showed that 81% of my students had less than a 70% mastery of the concepts (*N* = 78 and SD = 16). All but fifteen of my students needed significant instruction in vectors. See Figure 11 below.

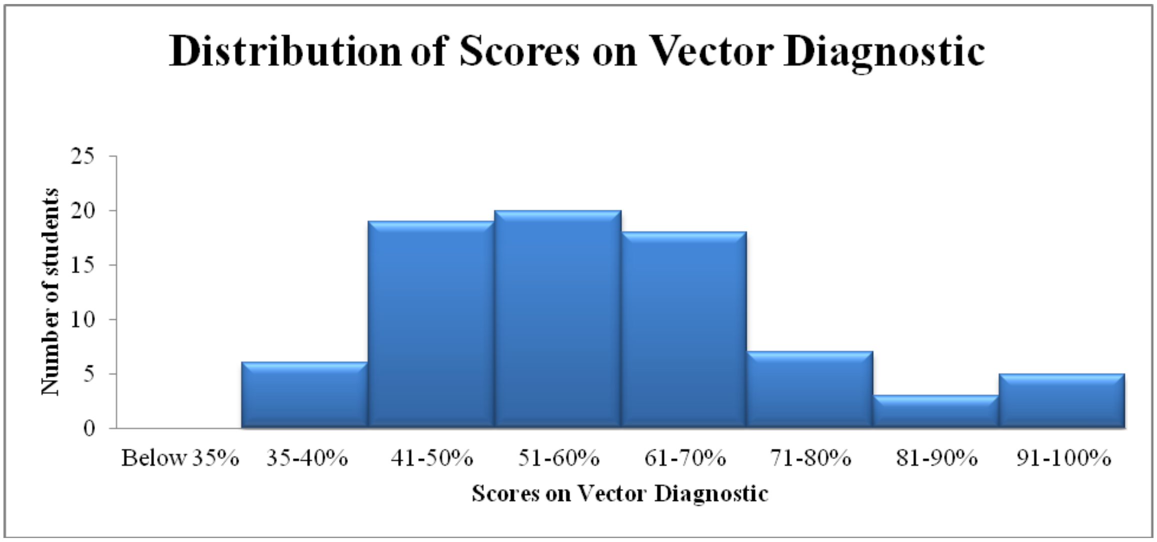


Figure 11. Distribution of Scores on Vector Diagnostic, (*N*=76, STD=16).

From the time of the vector diagnostic pre-test until the post-test the students had multiple activities utilizing the manipulatives as described in the treatment. I also assessed them on two physics units (forces and projectile motion) that rely heavily on visual/spatial abilities and vectors in particular. One trend that I noticed was a reversal of what I have seen in the past. Typically the students perform better on the forces test than they do on the projectile motion test; this year's projectile motion test (which is usually one of the more challenging topics) had a higher average than the forces test. Figure 12 below is a side-by-side comparison of the distributions of my 76 students' scores on the forces test and projectile motion test. It might be too soon to conclude this, but it appears that the bell curve distribution of the past is now an "on ramp to success" with the bulk of scores above the seventy-fifth percentile.

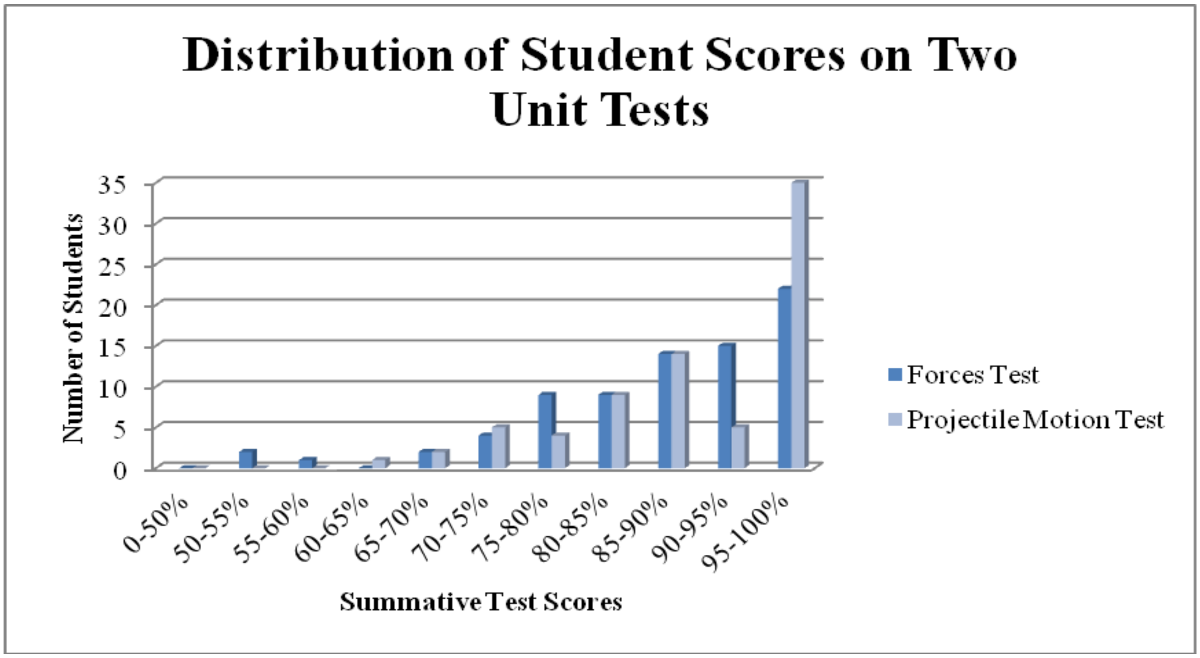


Figure 12. Distribution of Scores on Tests on Forces and Projectile Motion, (*N*=76).

Reflecting on my original action research questions and the evidence at hand I conclude that instruction in visual/spatial thinking has improved my students' ability to learn physics concepts as demonstrated by their larger than normal gains on the Force Concept Inventory and unit test scores. Visual/spatial thinking is something that can be taught, practiced and learned as evidenced in my students' performance on the pre-tests and post-tests of Spatial Abilities and the Vector assessments. The majority of students report having a positive attitude about the class as a result of having instruction that strengthens their visual/spatial skills by using manipulatives. There is statistical evidence of this effect in that enrollment in the second year course has increased by 28% (from 43 students to 55) for a constant enrollment in the first year course. Finally the effect on me as a teacher has been almost like having a second language with which I can communicate with my students. I noted 25 times in my lesson plans that I inserted the use of the cardboard vectors during instruction during the year. I noted in one of my reflections that I had to be sure to use the cardboard vectors when we were either doing something new with vectors, like exploring the concept of superposition, or when the students were likely to be rusty as they were after the unit on energy which focuses primarily on scalar (non-directional) quantities. Besides these anecdotal reflections I did note some quantitative data relating the effect of the research on me; my investment in *time*.

Table 3
Time Allocation

Time spent creating manipulatives and planning their implementation	3 hours
Time spent using the vector manipulatives during in school and after school remediation	11 hours
Time spent using a new instructional method during the treatment	5.8 hours
Time spent administering pre-tests and post-tests for research purposes	2.3 hours

The only hours in the table above that were at a high cost to me were the 2.3 class hours that I spent administering the pre-tests and post-tests: Spatial Ability twice, two Vector assessments and Force Concept Inventory twice. That data was the most useful in providing insight to my students' progress during the treatment.

As an instructor with strong visual/spatial skills myself, it has been difficult over my fifteen years of teaching physics to teach students about something that I understood so intuitively. Now that I have the manipulative tools to guide them, I feel that I can reach more students.

INTERPRETATION AND CONCLUSION

To conclude, concerning my research question on the effect of instruction in visual/spatial thinking skills on learning of physics concepts; I feel that I have seen evidence of a positive effect of instruction in visual/spatial skills on my students' ability to learn physics. As evidence, I re-state the impressive results of 1) the students' performance on the creation of their net force diagrams on the static equilibrium lab and 2) the test on projectile motion with only three students scoring below 70%. As for the secondary questions such as the effect of instruction in visual/spatial thinking skills on students' visual/spatial abilities; my students made impressive gains in their visual/spatial thinking skills as evidenced by the comparison of the pre-test and post-test results where all but two of the 76 students had significant normalized gain (actual percent increase divided by potential percent increase) with a mean of 50%. I observed during this year's unit on current electricity the students were more adept at using the schematic diagrams to assemble the electrical components for circuit analysis than they have been in past years; this improved spatial ability, "Making connections between real objects and drawings, photographs, or media images that represent the objects", (McCormack & Mason, 2000) might be due to the treatment that these students experienced. I think that I appreciated this gain more than the students might have as I answered far fewer questions and we blew far fewer fuses in the ammeters, only 2 blown fuses this year as opposed to up to 10 in past years for a similar number of students.

The students did express their appreciation in my attempt to improve their learning. At the end of each quarter the students responded to a survey about: their progress, my instruction, and their attitudes about the course. As was previously discussed, eighty-eight percent of my students responded that the use of manipulatives in the course caused them to have a more positive attitude about the class. My observations were that the manipulatives were very helpful in explaining concepts to students when I needed to give them extra help and when students were explaining concepts to one another.

Giving students this extra help with their physics concepts and their visual/spatial thinking skills was both demanding and rewarding for me. As I reviewed my own reflections I noticed a recurring theme: *time.* At first it was about the time invested in planning and creating the various manipulatives that I used. Later I noticed the time saving element of more effective teaching. The time that I took to create the manipulatives and plan to use them was minimized for me (to only three hours) because I have a student lab assistant. As I tally up the time that I spent tutoring my students with the intervention materials after school and during our school's intervention periods, the total time is just shy of 11 hours. I built instructional time into my lesson plans during the lessons during which the physics concepts included vector quantities totaling 350 minutes of new instruction. To avoid falling behind in my curriculum I substituted the new treatment for the old instructional method whenever possible. I also used class time to administer the pre-tests and post-tests which totaled 140 minutes of class time during the course of the treatment. Although the students' improvement on the spatial ability test and their gains on the Force Concept Inventory were very exciting to me, I cannot deny that there was physics content that I did not have time to teach.

VALUE

The benefit of this effort to me has been a deeper understanding of my students' strengths and weaknesses. I was able to identify the students who would likely struggle to grasp physics concepts from the moment I evaluated the students' performance on the visual/spatial diagnostic test on the first day of school. Early identification allowed me to intervene more efficiently and, in some units of study, it reduced the number of second chance assessments. Last year 26% (*N*=78) of my students took a second chance test on the forces unit while this year that percent decreased to 19% (*N*=76). I plan to discuss this type of improvement with my fellow physics instructors and will recommend the following changes to our curriculum: 1) To administer the visual-spatial skill diagnostic assessment to all physics students on the first day of school; and 2) To create a set of physics-related visual/spatial thinking (VST) materials to enhance the students' VST skills such as the cardboard vectors that I used during this treatment. The two most compelling pieces of evidence that support this decision are the students' improvement on the Spatial Ability Test seen on page 19 and the Force Concept Inventory seen on page 21.

Based on what I learned in this research, in the future I will definitely focus on my physics students' spatial abilities by assessing them at the beginning of the school year and using the cardboard vector manipulatives to instruct and remediate. I may even consider asking the instructors of the feeder courses (the chemistry teachers) to administer the Spatial Ability test to their sophomores as an aid in course selection. One interesting point that arose during data analysis and student interviews was the gender gap and possible cause, childhood play. I hope to explore that further by adding even more activities to my lessons such as a visit to a playground during the units on motion and forces. It may sound counter-intuitive to return to manipulatives (or the playground) to enhance our students' achievement in science, but to move forward in STEM, that may be where our answers lie.

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APPENDICES

APPENDIX A

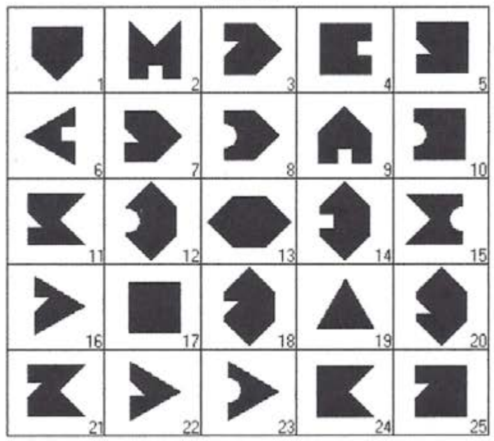
SPATIAL ABILITY DIAGNOSTIC TEST

Test 1—45 Questions

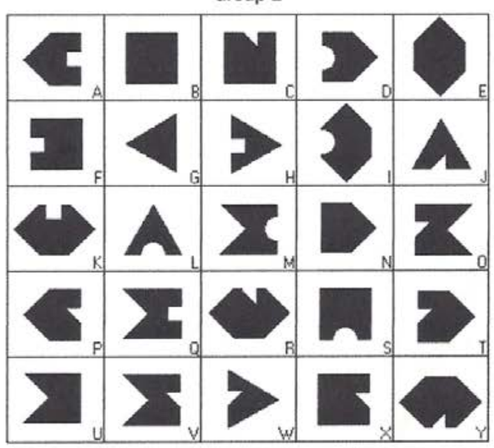
Answer as many questions as you can in 20 minutes.

The shapes in Group 1 and Group 2 are identical, although some of them may be rotated. Which shape in Group 2 corresponds to the shapes (1 to 25) in Group 1?

Group 1



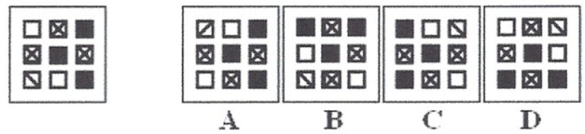
Group 2



1)	2)	3)	4)	5)
6)	7)	8)	9)	10)
11)	12)	13)	14)	15)
16)	17)	18)	19)	20)
21)	22)	23)	24)	25)

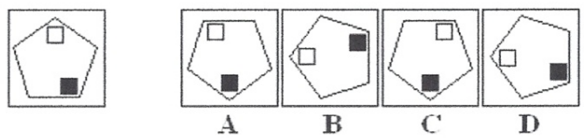
In the figures shown below, one of the shapes (A-D) is identical to the first figure but has been rotated.

26) Which figure is identical to the first?



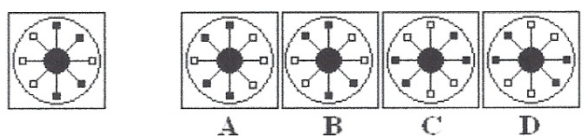
A B C D

27) Which figure is identical to the first?



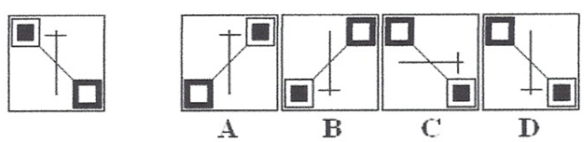
A B C D

28) Which figure is identical to the first?



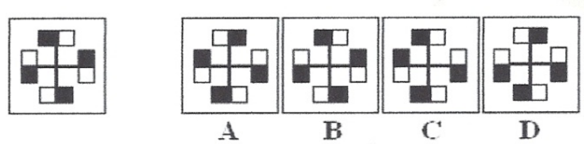
A B C D

29) Which figure is identical to the first?



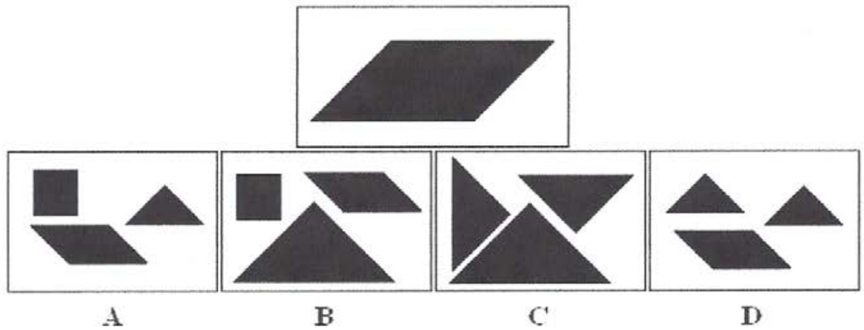
A B C D

30) Which figure is identical to the first?



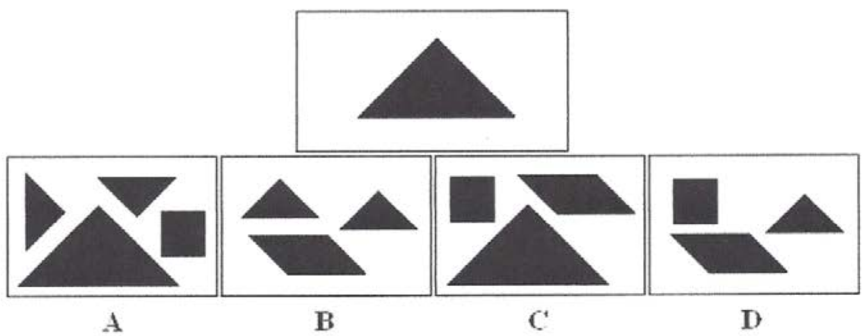
A B C D

31) Which group of shapes can be assembled to make the shape shown?



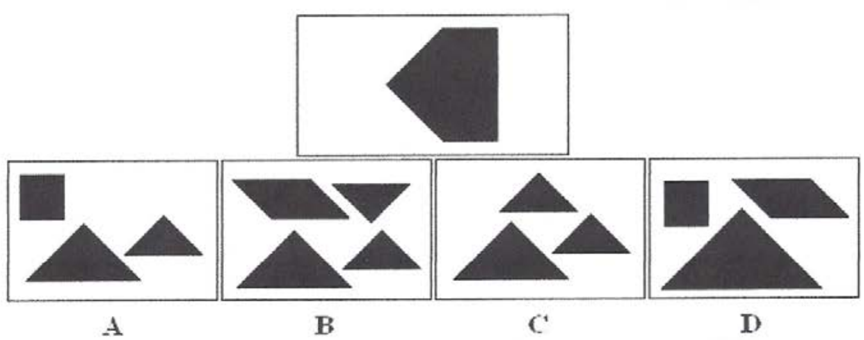
A B C D

32) Which group of shapes can be assembled to make the shape shown?



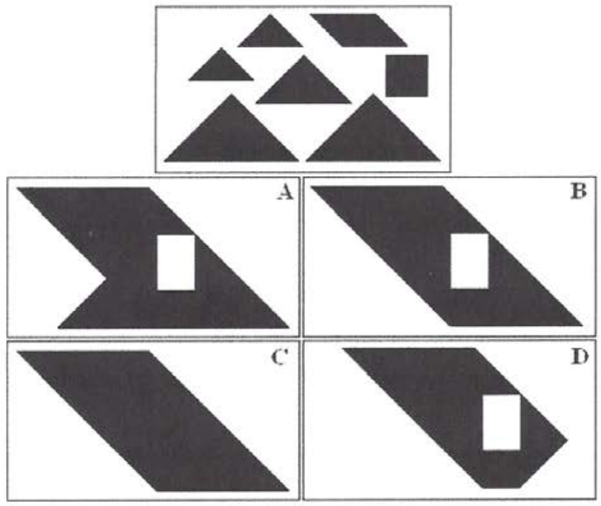
A B C D

33) Which group of shapes can be assembled to make the shape shown?



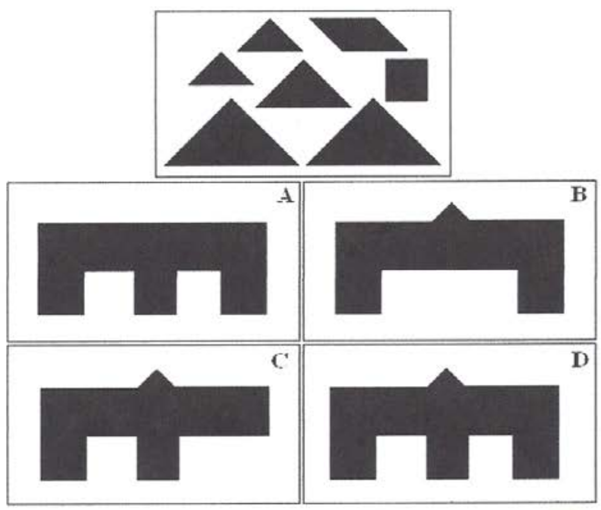
A B C D

34) Which shape can be assembled using all of the individual shapes shown?



A B C D

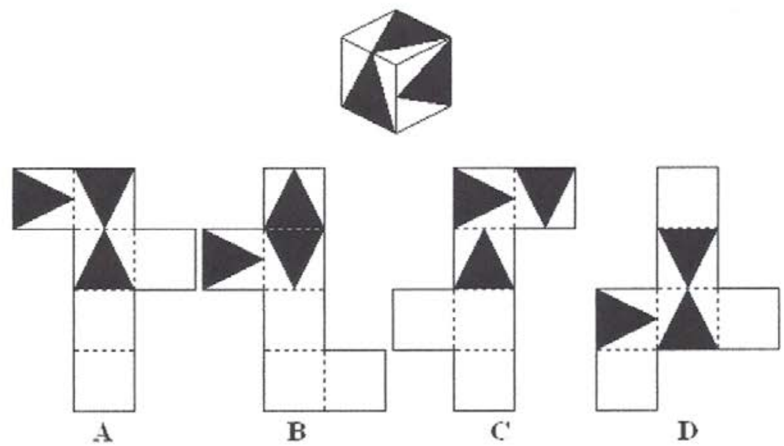
35) Which shape can be assembled using all of the individual shapes shown?



A B C D

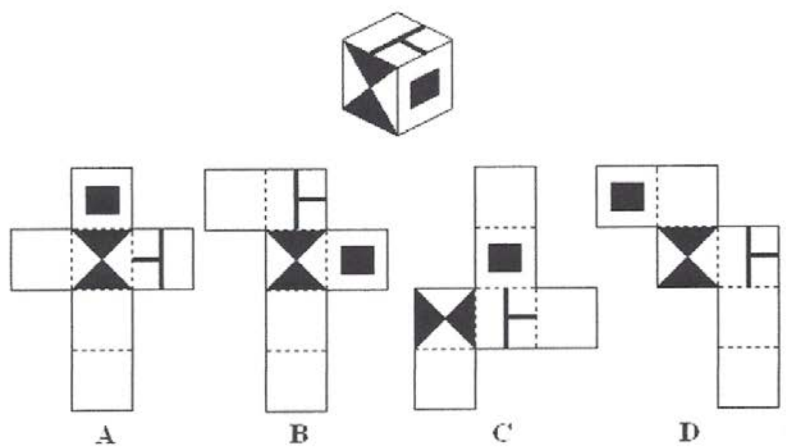
Which pattern can be folded to make the cube shown?

36)



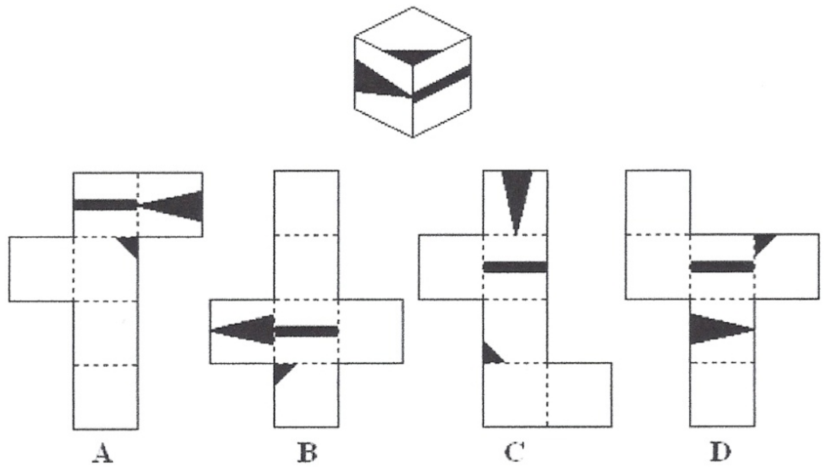
A B C D

37)



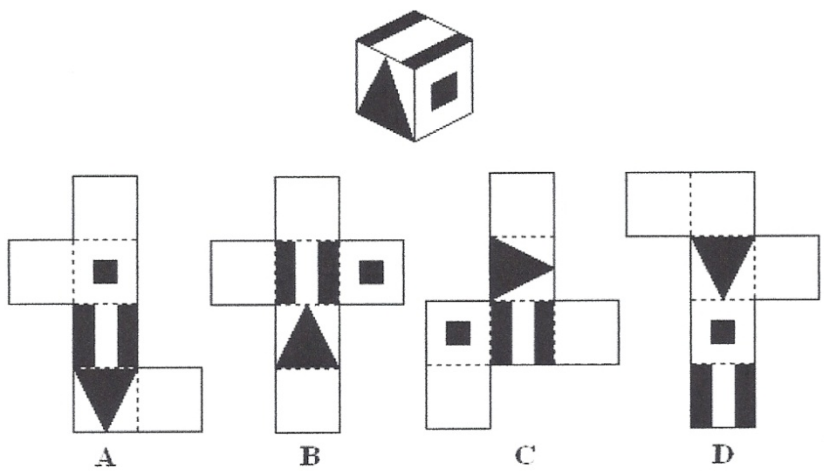
A B C D

38)



A B C D

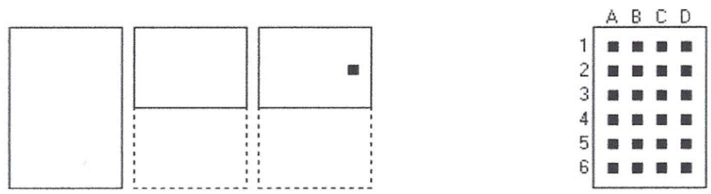
39)



A B C D

The drawings show a sheet of paper which has been folded. The dashed lines indicate the whole sheet, each drawing represents a single fold. The black square shows where a hole was punched. Where do the holes appear when the sheet is unfolded?

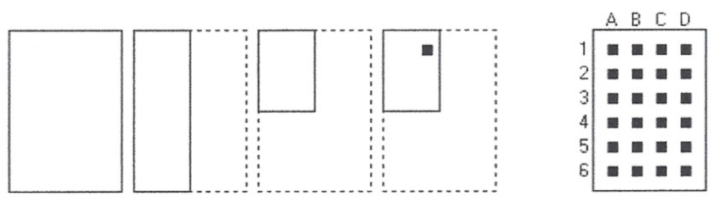
40)



A	B	C	D
2C,5C	2D,5D	3D,3D	2C,2D

A B C D

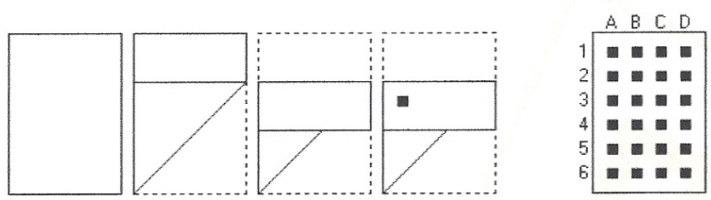
41)



A	B	C	D
1B,1C,5B,5C	2B,2C,5B,5C	1B,2C,6B,6C	1B,1C,6B,6C

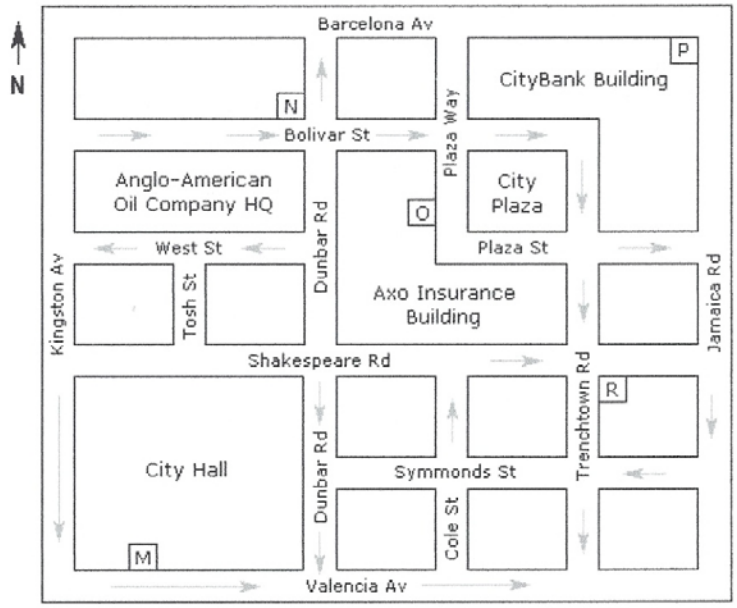
A B C D

42)



A	B	C	D
3A,2A,6D	3A,5A,6D	3A,5A,3D	3A,2A

A B C D



43) Officer Perez is in Tosh St with City Hall to her right. What direction is she facing?

A	B	C	D
North	South	East	West

44) She turns and walks to the junction with West St. She then turns right and walks to the next junction before turning left. Where is location 'O' in relation to her position?

A	B	C	D
North	South	East	West

45) Officer Martinez starts from location 'M' and proceeds as follows: left onto Valencia Av - heading East, second left - heading North, second right - heading East, second left - heading North. He proceeds North for two blocks. What is his location?

A	B	C	D
N	O	R	P

End of Spatial Reasoning—Test 1

APPENDIX B

FORCE CONCEPT INVENTORY

1. Two metal balls are the same size but one weighs twice as much as the other. The balls are dropped from the roof of a single story building at the same instant of time. The time it takes the balls to reach the ground below will be:
   (A) about half as long for the heavier ball as for the lighter one.
   (B) about half as long for the lighter ball as for the heavier one.
   (C) about the same for both balls.
   (D) considerably less for the heavier ball, but not necessarily half as long.
   (E) considerably less for the lighter ball, but not necessarily half as long.

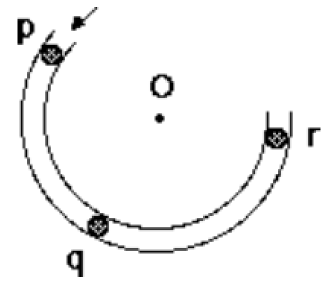
2. The two metal balls of the previous problem roll off a horizontal table with the same speed. In this situation:
   (A) both balls hit the floor at approximately the same horizontal distance from the base of the table.
   (B) the heavier ball hits the floor at about half the horizontal distance from the base of the table than does the lighter ball.
   (C) the lighter ball hits the floor at about half the horizontal distance from the base of the table than does the heavier ball.
   (D) the heavier ball hits the floor considerably closer to the base of the table than the lighter ball, but not necessarily at half the horizontal distance.
   (E) the lighter ball hits the floor considerably closer to the base of the table than the heavier ball, but not necessarily at half the horizontal distance.

3. A stone dropped from the roof of a single story building to the surface of the earth:
   (A) reaches a maximum speed quite soon after release and then falls at a constant speed thereafter.
   (B) speeds up as it falls because the gravitational attraction gets considerably stronger as the stone gets closer to the earth.
   (C) speeds up because of an almost constant force of gravity acting upon it.
   (D) falls because of the natural tendency of all objects to rest on the surface of the earth.
   (E) falls because of the combined effects of the force of gravity pushing it downward and the force of the air pushing it downward.

4. A large truck collides head-on with a small compact car. During the collision:
   (A) the truck exerts a greater amount of force on the car than the car exerts on the truck.
   (B) the car exerts a greater amount of force on the truck than the truck exerts on the car.
   (C) neither exerts a force on the other, the car gets smashed simply because it gets in the way of the truck.
   (D) the truck exerts a force on the car but the car does not exert a force on the truck.
   (E) the truck exerts the same amount of force on the car as the car exerts on the truck.

USE THE STATEMENT AND FIGURE BELOW TO ANSWER THE NEXT TWO QUESTIONS (5 and 6).

The accompanying figure shows a frictionless channel in the shape of a segment of a circle with center at "O". The channel has been anchored to a frictionless horizontal table top. You are looking down at the table. Forces exerted by the air are negligible. A ball is shot at high speed into the channel at "p" and exits at "r."

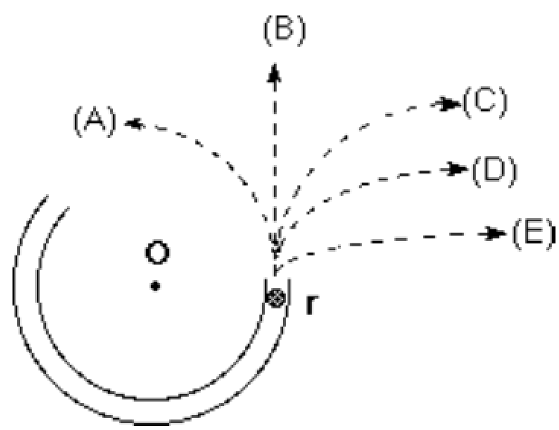


5. Consider the following distinct forces:
   1. A downward force of gravity.
   2. A force exerted by the channel pointing from q to O.
   3. A force in the direction of motion.
   4. A force pointing from O to q.

   Which of the above forces is (are) acting on the ball when it is within the frictionless channel at position "q"?

   (A) 1 only.
   (B) 1 and 2.
   (C) 1 and 3.
   (D) 1, 2, and 3.
   (E) 1, 3, and 4.

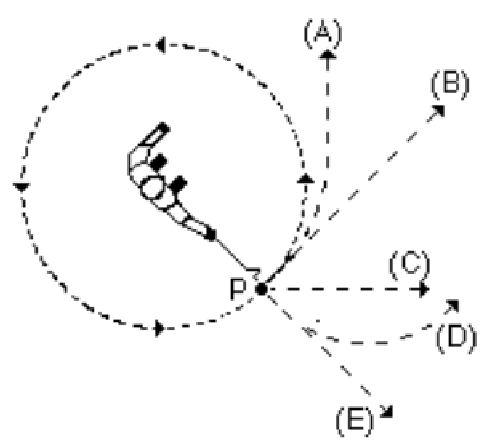
6. Which path in the figure at right would the ball most closely follow after it exits the channel at "r" and moves across the frictionless table top?



7. A steel ball is attached to a string and is swung in a circular path in a horizontal plane as illustrated in the accompanying figure.

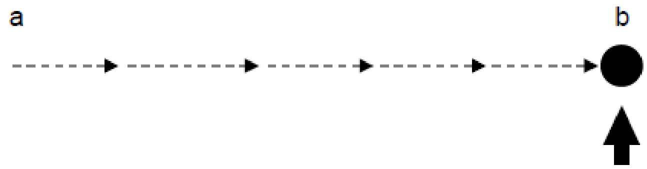
   At the point P indicated in the figure, the string suddenly breaks near the ball.

   If these events are observed from directly above as in the figure, which path would the ball most closely follow after the string breaks?

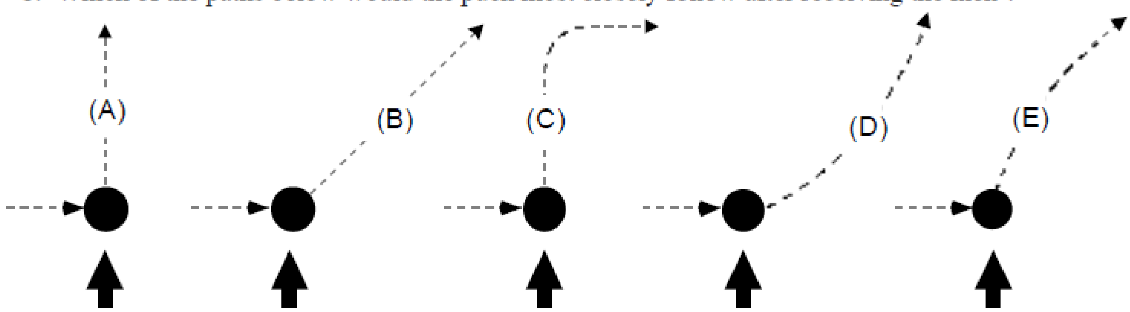


USE THE STATEMENT AND FIGURE BELOW TO ANSWER THE NEXT FOUR QUESTIONS (8 through 11).

The figure depicts a hockey puck sliding with constant speed v_o in a straight line from point "a" to point "b" on a frictionless horizontal surface. Forces exerted by the air are negligible. You are looking down on the puck. When the puck reaches point "b," it receives a swift horizontal kick in the direction of the heavy print arrow. Had the puck been at rest at point "b," then the kick would have set the puck in horizontal motion with a speed v_k in the direction of the kick.



8. Which of the paths below would the puck most closely follow after receiving the kick ?

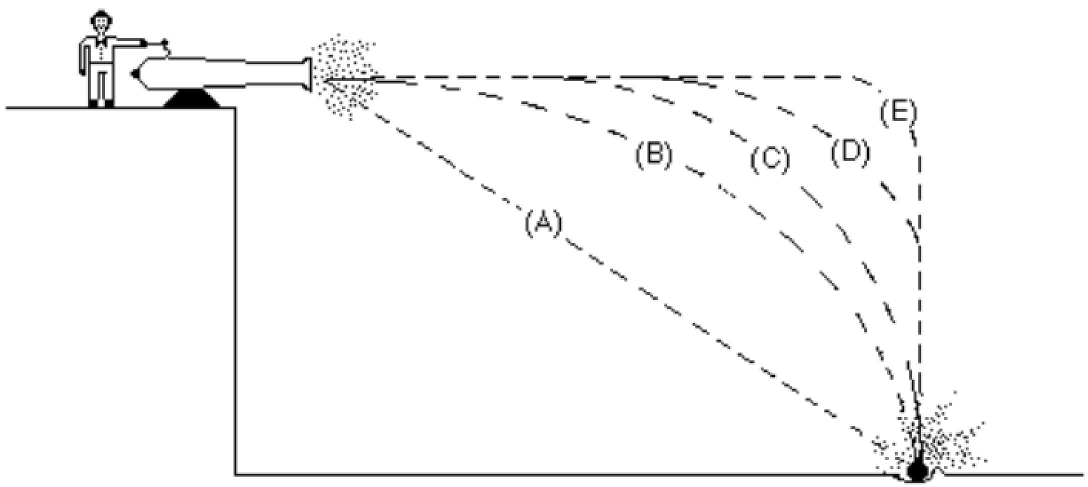


9. The speed of the puck just after it receives the kick is:
   (A) equal to the speed "v_o" it had before it received the kick.
   (B) equal to the speed "v_k" resulting from the kick and independent of the speed "v_o".
   (C) equal to the arithmetic sum of the speeds "v_o" and "v_k".
   (D) smaller than either of the speeds "v_o" or "v_k".
   (E) greater than either of the speeds "v_o" or "v_k", but less than the arithmetic sum of these two speeds.

10. Along the frictionless path you have chosen in question 8, the speed of the puck after receiving the kick:
    (A) is constant.
    (B) continuously increases.
    (C) continuously decreases.
    (D) increases for a while and decreases thereafter.
    (E) is constant for a while and decreases thereafter.

11. Along the frictionless path you have chosen in question 8, the main force(s) acting on the puck after receiving the kick is (are):
    (A) a downward force of gravity.
    (B) a downward force of gravity, and a horizontal force in the direction of motion.
    (C) a downward force of gravity, an upward force exerted by the surface, and a horizontal force in the direction of motion.
    (D) a downward force of gravity and an upward force exerted by the surface.
    (E) none. (No forces act on the puck.)

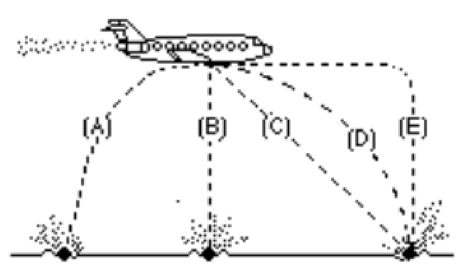
12. A ball is fired by a cannon from the top of a cliff as shown in the figure below. Which of the paths would the cannon ball most closely follow?



13. A boy throws a steel ball straight up. Consider the motion of the ball only after it has left the boy's hand but before it touches the ground, and assume that forces exerted by the air are negligible. For these conditions, the force(s) acting on the ball is (are):
   (A) a downward force of gravity along with a steadily decreasing upward force.
   (B) a steadily decreasing upward force from the moment it leaves the boy's hand until it reaches its highest point; on the way down there is a steadily increasing downward force of gravity as the object gets closer to the earth.
   (C) an almost constant downward force of gravity along with an upward force that steadily decreases until the ball reaches its highest point; on the way down there is only a constant downward force of gravity.
   (D) an almost constant downward force of gravity only.
   (E) none of the above. The ball falls back to ground because of its natural tendency to rest on the surface of the earth.

14. A bowling ball accidentally falls out of the cargo bay of an airliner as it flies along in a horizontal direction.

   As observed by a person standing on the ground and viewing the plane as in the figure at right, which path would the bowling ball most closely follow after leaving the airplane?



USE THE STATEMENT AND FIGURE BELOW TO ANSWER THE NEXT TWO QUESTIONS (15 and 16).

A large truck breaks down out on the road and receives a push back into town by a small compact car as shown in the figure below.

15. While the car, still pushing the truck, is speeding up to get up to cruising speed:
    (A) the amount of force with which the car pushes on the truck is equal to that with which the truck pushes back on the car.
    (B) the amount of force with which the car pushes on the truck is smaller than that with which the truck pushes back on the car.
    (C) the amount of force with which the car pushes on the truck is greater than that with which the truck pushes back on the car.
    (D) the car's engine is running so the car pushes against the truck, but the truck's engine is not running so the truck cannot push back against the car. The truck is pushed forward simply because it is in the way of the car.
    (E) neither the car nor the truck exert any force on the other. The truck is pushed forward simply because it is in the way of the car.

16. After the car reaches the constant cruising speed at which its driver wishes to push the truck:
    (A) the amount of force with which the car pushes on the truck is equal to that with which the truck pushes back on the car.
    (B) the amount of force with which the car pushes on the truck is smaller than that with which the truck pushes back on the car.
    (C) the amount of force with which the car pushes on the truck is greater than that with which the truck pushes back on the car.
    (D) the car's engine is running so the car pushes against the truck, but the truck's engine is not running so the truck cannot push back against the car. The truck is pushed forward simply because it is in the way of the car.
    (E) neither the car nor the truck exert any force on the other. The truck is pushed forward simply because it is in the way of the car.

17. An elevator is being lifted up an elevator shaft at a constant speed by a steel cable as shown in the figure below. All frictional effects are negligible. In this situation, forces on the elevator are such that:

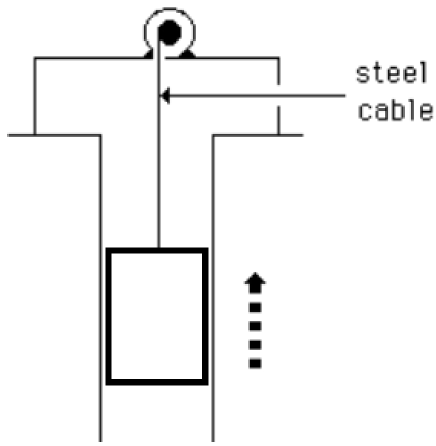
(A) the upward force by the cable is greater than the downward force of gravity.

(B) the upward force by the cable is equal to the downward force of gravity.

(C) the upward force by the cable is smaller than the downward force of gravity.

(D) the upward force by the cable is greater than the sum of the downward force of gravity and a downward force due to the air.

(E) none of the above. (The elevator goes up because the cable is being shortened, not because an upward force is exerted on the elevator by the cable).

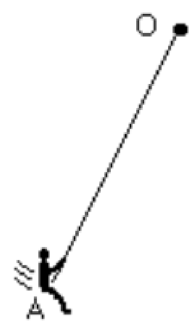


Elevator going up
at constant speed

18. The figure below shows a boy swinging on a rope, starting at a point higher than A.

Consider the following distinct forces:

1. A downward force of gravity.
2. A force exerted by the rope pointing from A to O.
3. A force in the direction of the boy's motion.
4. A force pointing from O to A.



Which of the above forces is (are) acting on the boy when he is at position A?

(A) 1 only.

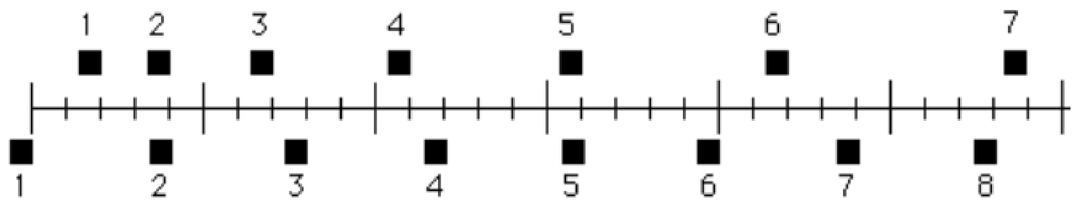
(B) 1 and 2.

(C) 1 and 3.

(D) 1, 2, and 3.

(E) 1, 3, and 4.

19. The positions of two blocks at successive 0.20-second time intervals are represented by the numbered squares in the figure below. The blocks are moving toward the right.



Do the blocks ever have the same speed?

(A) No.

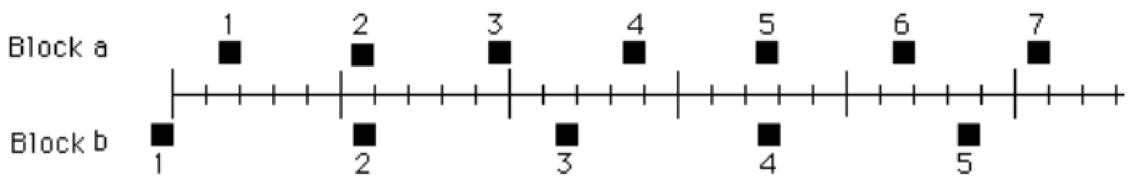
(B) Yes, at instant 2.

(C) Yes, at instant 5.

(D) Yes, at instants 2 and 5.

(E) Yes, at some time during the interval 3 to 4.

20. The positions of two blocks at successive 0.20-second time intervals are represented by the numbered squares in the figure below. The blocks are moving toward the right.



The accelerations of the blocks are related as follows:

(A) The acceleration of "a" is greater than the acceleration of " b".

(B) The acceleration of "a" equals the acceleration of "b". Both accelerations are greater than zero.

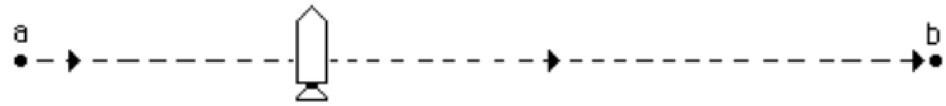
(C) The acceleration of "b" is greater than the acceleration of "a".

(D) The acceleration of "a" equals the acceleration of "b". Both accelerations are zero.

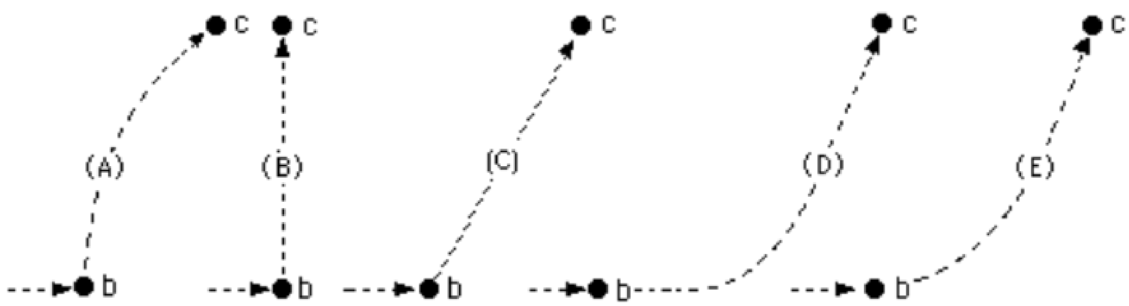
(E) Not enough information is given to answer the question.

USE THE STATEMENT AND FIGURE BELOW TO ANSWER THE NEXT FOUR QUESTIONS (21 through 24).

A rocket drifts sideways in outer space from point "a" to point "b" as shown below. The rocket is subject to no outside forces. Starting at position "b", the rocket's engine is turned on and produces a constant thrust (force on the rocket) at right angles to the line "ab". The constant thrust is maintained until the rocket reaches a point "c" in space.

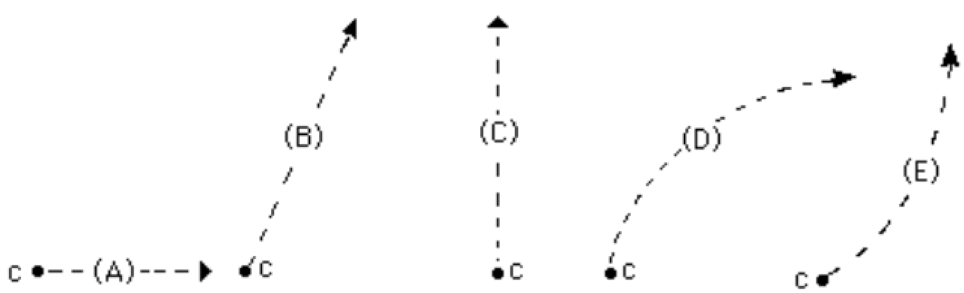


21. Which of the paths below best represents the path of the rocket between points "b" and "c"?



22. As the rocket moves from position"b" to position "c" its speed is:
    (A) constant.
    (B) continuously increasing.
    (C) continuously decreasing.
    (D) increasing for a while and constant thereafter.
    (E) constant for a while and decreasing thereafter.

23. At point "c" the rocket's engine is turned off and the thrust immediately drops to zero. Which of the paths below will the rocket follow beyond point "c"?



24. Beyond position "c" the speed of the rocket is:
    (A) constant.
    (B) continuously increasing.
    (C) continuously decreasing.
    (D) increasing for a while and constant thereafter.
    (E) constant for a while and decreasing thereafter.

25. A woman exerts a constant horizontal force on a large box. As a result, the box moves across a horizontal floor at a constant speed "v_o".

    The constant horizontal force applied by the woman:

    (A) has the same magnitude as the weight of the box.

    (B) is greater than the weight of the box.

    (C) has the same magnitude as the total force which resists the motion of the box.

    (D) is greater than the total force which resists the motion of the box.

    (E) is greater than either the weight of the box or the total force which resists its motion.

26. If the woman in the previous question doubles the constant horizontal force that she exerts on the box to push it on the same horizontal floor, the box then moves:

    (A) with a constant speed that is double the speed "v_o" in the previous question.

    (B) with a constant speed that is greater than the speed "v_o" in the previous question, but not necessarily twice as great.

    (C) for a while with a speed that is constant and greater than the speed "v_o" in the previous question, then with a speed that increases thereafter.

    (D) for a while with an increasing speed, then with a constant speed thereafter.

    (E) with a continuously increasing speed.

27. If the woman in question 25 suddenly stops applying a horizontal force to the box, then the box will:

    (A) immediately come to a stop.

    (B) continue moving at a constant speed for a while and then slow to a stop.

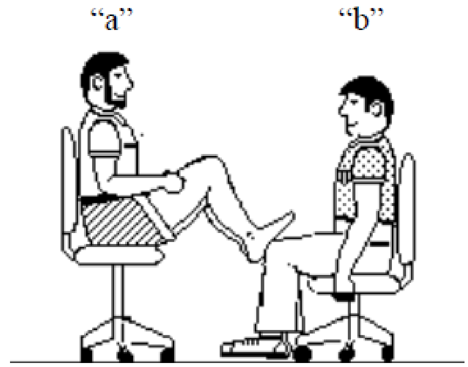
    (C) immediately start slowing to a stop.

    (D) continue at a constant speed.

    (E) increase its speed for a while and then start slowing to a stop.

28. In the figure at right, student "a" has a mass of 95 kg and student "b" has a mass of 77 kg. They sit in identical office chairs facing each other.

Student "a" places his bare feet on the knees of student "b", as shown. Student "a" then suddenly pushes outward with his feet, causing both chairs to move.



During the push and while the students are still touching one another:

(A) neither student exerts a force on the other.

(B) student "a" exerts a force on student "b", but "b" does not exert any force on "a".

(C) each student exerts a force on the other, but "b" exerts the larger force.

(D) each student exerts a force on the other, but "a" exerts the larger force.

(E) each student exerts the same amount of force on the other.

29. An empty office chair is at rest on a floor. Consider the following forces:

1. A downward force of gravity.
2. An upward force exerted by the floor.
3. A net downward force exerted by the air.

Which of the forces is (are) acting on the office chair?

(A) 1 only.

(B) 1 and 2.

(C) 2 and 3.

(D) 1, 2, and 3.

(E) none of the forces. (Since the chair is at rest there are no forces acting upon it.)

30. Despite a very strong wind, a tennis player manages to hit a tennis ball with her racquet so that the ball passes over the net and lands in her opponent's court.

Consider the following forces:

1. A downward force of gravity.
2. A force by the "hit".
3. A force exerted by the air.

Which of the above forces is (are) acting on the tennis ball after it has left contact with the racquet and before it touches the ground?

(A) 1 only.

(B) 1 and 2.

(C) 1 and 3.

(D) 2 and 3.

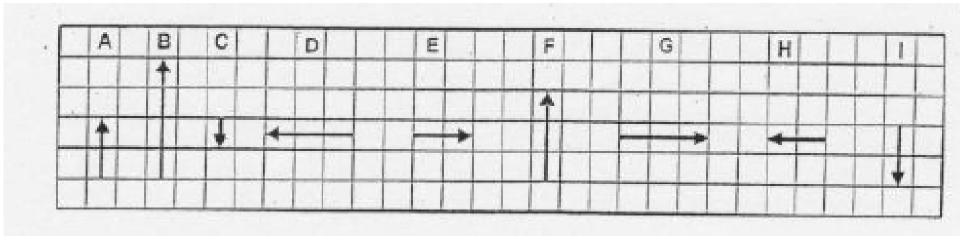
(E) 1, 2, and 3.

APPENDIX C

VECTOR DIAGNOSTIC

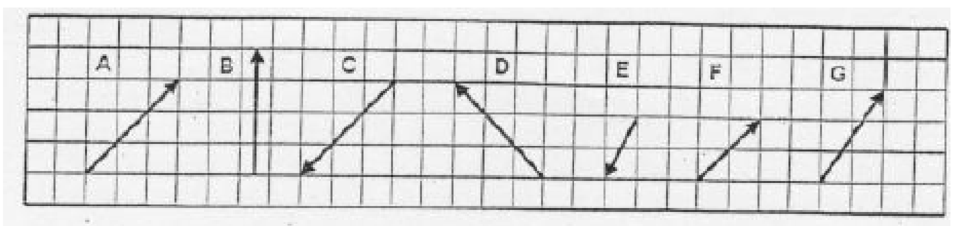
Vector Concept Diagnostic

1. Consider the list below and write down all vectors that have the same magnitude as each other. For instance, if vectors $\vec{W}$ and $\vec{X}$ have the same magnitude, and the vectors $\vec{Y}$, $\vec{Z}$, and $\vec{A}$ have the same magnitudes as each other (but different from $\vec{W}$ and $\vec{X}$) then you should write the following: $|\vec{W}| = |\vec{X}|, |\vec{Y}| = |\vec{Z}| = |\vec{A}|$.



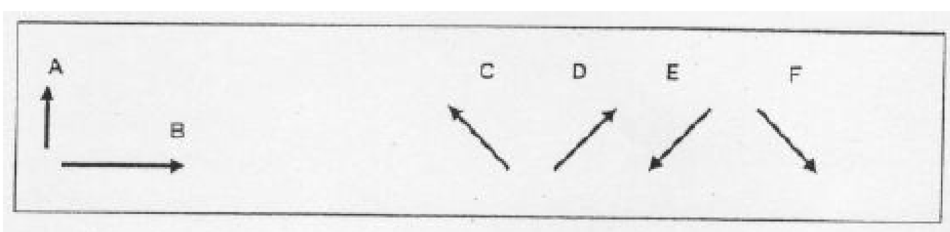
Answer____

2. List all vectors that have the same direction as vector $\vec{A}$. If there are none, please explain why.



Answer________________________

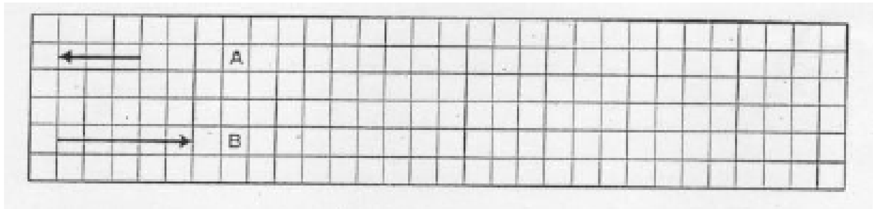
3. Below shown are vectors $\vec{A}$ and $\vec{B}$. Consider $\vec{R}$, the vector sum (the "resultant") of $\vec{A}$ and $\vec{B}$. Which of the other four vectors shown ($\vec{C}, \vec{D}, \vec{E}, \vec{F}$) has most nearly the *same direction* as $\vec{R}$?



Answer________________________

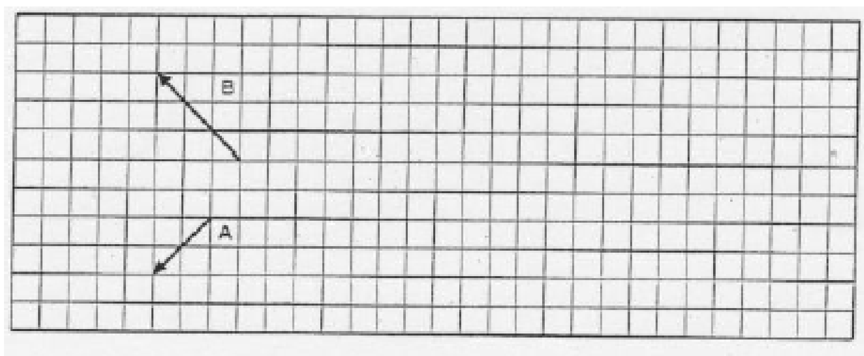
N-L. Nguyen and D. Metzer. (2003). "Initial understanding of vector concepts among students in introductory physics courses." *Am. J. Phys.* **71**(6), 630-638.

4. In the space below, draw $\vec{R}$ where $\vec{R} = \vec{A} + \vec{B}$. Clearly label it as vector $\vec{R}$. Explain your work.

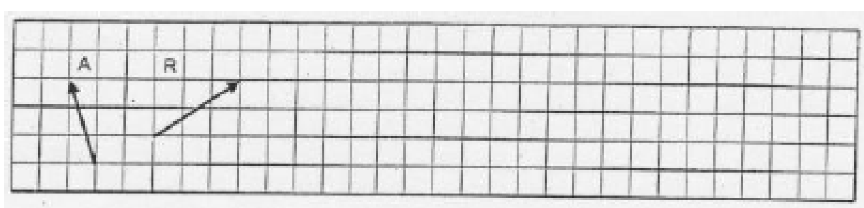


Explanation____

5. In the figure below, there are two vectors $\vec{A}$ and $\vec{B}$. Draw a vector $\vec{R}$ that is the sum of the two, (i.e., $\vec{R} = \vec{A} + \vec{B}$). Clearly label the resultant vector as $\vec{R}$.



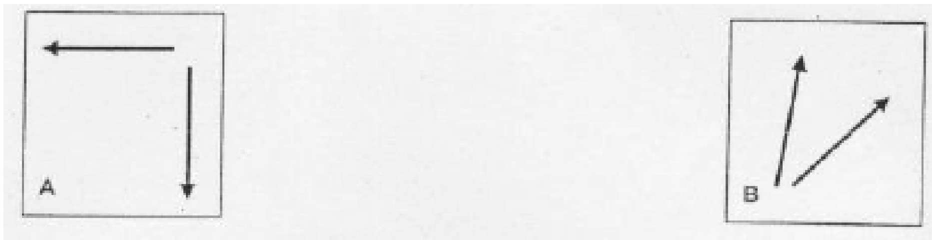
6. In the figure below, a vector $\vec{R}$ is shown that is the **net resultant** of two other vectors $\vec{A}$ and $\vec{B}$ (i.e., $\vec{R} = \vec{A} + \vec{B}$). Find the vector $\vec{B}$ that when added to $\vec{A}$, produces $\vec{R}$. DO NOT try to combine or add $\vec{A}$ and $\vec{R}$ directly together! Briefly explain your answer.



Explanation____

N-L. Nguyen and D. Metzer. (2003). "Initial understanding of vector concepts among students in introductory physics courses." *Am. J. Phys.* **71**(6), 630-638.

7. In the boxes below are two pairs of vectors, pair A and pair B. (All arrows have the same length). Consider the magnitude of the **resultant** (the vector sum) of each pair of vectors. Is the magnitude of the resultant of pair A, *larger than, smaller than*, or the *same* as the magnitude of the resultant of pair B? Write an explanation justifying this conclusion.

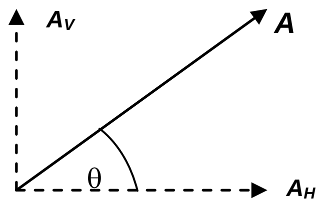


Explanation____

We report the results of an investigation into physics students' understanding of vector addition, magnitude, and direction for problems presented in graphical form. A seven-item quiz, including free-response problems, was administered in all introductory general physics courses during the 2000/2001 academic year at Iowa State. Responses were obtained from 2031 students during the first week of class. We found that more than one quarter of students beginning their second semester of study in the calculus-based physics course, and more than half of those beginning the second semester of the algebra-based sequence, were unable to carry out two-dimensional vector addition. Although the total scores on the seven-item quiz were somewhat better for students in their second semester of physics in comparison to students in their first semester, many students retained significant conceptual difficulties regarding vector methods that are heavily employed throughout the physics curriculum. © 2003 American Association of Physics Teachers.

APPENDIX D

FORMATIVE ASSESSMENT ON VECTORS



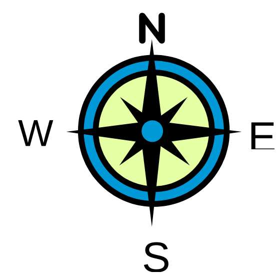
$A_H = A\cos\theta$
$A_V = A\sin\theta$

Name ____________________

Date __________ Period _____

Formative Assessment on Vectors and Scaling

1. Using a scale of 1cm = 15ms^{-1}, draw a vector that represents 60.m·s^{-1} at an angle of 25 ° above the horizontal.



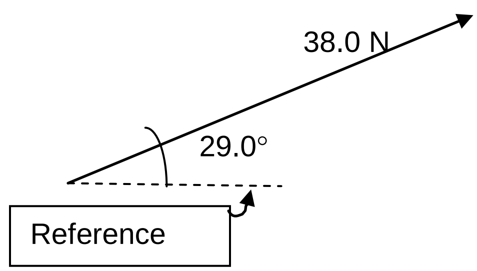
2. A physics student walks 3.50 m north then 6.50 m east.

   a) Draw a sketch of the vector addition including the resultant.

   b) Calculate student's resulting displacement (resultant).

   c) **Calculate** the angle that the resultant makes with the vector that points **north**.

3. For the force vector (in Newtons, N) sketched below:
   a) Draw the x and y components.
   b) Calculate the x and y components of the force.



   c) Use Pythagorean Theorem to check if the numbers that you calculated in part (b) make sense.

APPENDIX E

FORMATIVE ASSESSMENT ON EQUILIBRIUM

Formative Assessment on Translational Equilibrium

1. A woman exerts a constant horizontal force on a large box. As a result the box moves across the floor at a constant speed *"v"*. The constant horizontal force applied by the woman….
   a. Has the same magnitude as the weight of the box.
   b. Is greater than the weight of the box
   c. Has the same magnitude as the total force which resists the motion of the box.
   d. Is greater than the total force which resists the motion of the box.

2. If the woman in the previous question suddenly stops applying a horizontal force on the box, then the box will:
   a. Immediately come to a stop
   b. Immediately begin slowing to a stop
   c. Continue moving at constant speed for a while and then slow to a stop.
   d. Continue at constant speed.

3. A 0.170-kg hockey puck is sliding on the ice to the right at a constant velocity of 25 $m \cdot s^{-1}$. If friction is negligible, (small enough to be considered to be zero), determine the size of the force that keeps the puck moving.
   a. 250 N
   b. 25 N
   c. 1.7 N
   d. 0.0 N

4. The weight of wheeled recycling bin is 475 N. Working against friction, a person pushes horizontally on the bin moving it at a constant velocity of 0.67 $m \cdot s^{-1}$. The horizontal pushing force is 20.0 N.

a. Draw a free-body diagram of the bin.

b. Calculate the size of the friction force opposing the motion.