# New Approaches in Teaching Undergraduate Dynamics

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**ABSTRACT**
In order to enhance a first course in dynamics, instructors at the United States Air Force Academy have supplemented the class with demonstrations, laboratories, computational problems, and student presentations. Goals of the enhancement are to increase student motivation and understanding. Initial results may not show that students perform better overall, but motivation and interest levels are definitely improved and long-term appreciation and understanding may be increased. Making dynamics more hands-on and "real" may help to make it a less dreaded course without "dumbing down" the content.

**INTRODUCTION**
A first course in dynamics is often daunting for the typical undergraduate student. It brings together basic Newtonian physics and an array of mathematical concepts including vector algebra, geometry, trigonometry, and calculus, all of which can be quite abstract. Also, dynamic behavior is often non-intuitive. Students can get lost in the computations and lose (or never gain) insight into and appreciation for the power and relevance of dynamic analysis. Too often, undergraduate dynamics is only a number crunching exercise where students utilize equations without ever really understanding the terms within those equations and the implication of the results. At the U.S. Air Force Academy (USAFA), we are attempting to give cadets a better physical feel for and experience with the laws of dynamics.

The USAFA has a significantly different population of student compared to the typical university or college. The differences do not come so much from aptitude or motivation but from the constraints of the Academy. The student's time at the USAFA is much more in demand, as they are required to graduate from programs with typically 155 semester hours in no longer than four years. They are also loaded with military, leadership, and athletic requirements. It is not unusual for students to have less than an hour free every other day that they can use to take advantage of "extra instruction" (office hours). The students have little time to be critical thinkers regarding their academic endeavors.

Fortunately, dynamics is scheduled in a two-hour class period every other academic day at the USAFA. We have taken advantage of this extra hour by adding some laboratories, physical demonstrations, and student presentations to our course. Other non-traditional assignments include computational mechanics problems and a three-dimensional kinematics design project. The primary motivation behind these additional assignments are (a) to increase student interest and motivation, (b) to aid in student learning and understanding, and (c) to provide the students with a better appreciation of real-world applications of dynamics.

For the first laboratory, we have the cadets build and fire model rockets. The rocket laboratory helps them understand projectile motion problems and their associated assumptions. After covering rigid body kinetics, labs that are more interesting can be performed. The first rigid body lab involves a catapult, where cadets fire a raw egg towards a target. Analysis involves both work-energy methods to determine initial projectile speed and Newton's laws to determine the force acting on the catapult pin (hinge). The second rigid body lab utilizes a Charpy test machine, where an impact pendulum breaks a small metal test specimen. Work-energy methods are utilized to experimentally determine the mass moment of inertia of the pendulum. The laboratories are complemented by presentations of real-life dynamics problems. Pairs of cadets choose a topic of interest and perform dynamic analyses. Presentation topics include sporting events, impact problems, and vehicle crashes. Finally, several in-class demonstrations have been developed to help the cadets understand fundamental dynamic concepts, such as the difference between weight and mass on dynamic response. Data were collected on student subjective evaluations of the laboratories, presentations, and demonstrations. The combination of labs, real-life presentations, and demonstrations hopefully provide the students with a greater physical understanding of dynamics and problem-solving methods.

Each area of interest will be presented, with a brief description of student survey results. The students scored the various projects on a five-point Likert scale shown below:

**Table 1 - Five Point Likert Scale**

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree |

Students rated "interest/motivation" and "understanding" for each activity. We make recommendations for others that may wish to use these projects at the end of the project discussions. We also compare the motivation and understanding derived from the projects to that obtained from simply doing homework.

## ROCKET LAUNCH

One of the initial topics taught in the dynamics course is projectile motion, which most of the students have studied in physics courses. In order to give them a practical application of the material and to provide the students with the opportunity to have some fun, a model rocket project was created. Viking model rockets and Estes A8-3 engines (2.5 N-sec impulse) were used, which together cost about $3 per set. Students were grouped in teams of three and given extra time during the second hour of class to build the rockets. Because we wanted to have free flight, the nosecones were glued on to preclude parachute deployment. Bonus points were given for most aesthetic, most original, and biggest dud to aid student motivation.

Students were provided the initial flight angles and velocities (x and y) immediately after motor burnout (calculated with a Mathematica simulation). Their task was then to calculate the distances that the rockets would fly and their maximum heights, and to describe why experimental results would differ from their calculations. Later in the course, they were given the opportunity to include drag calculations in a computational mechanics program to obtain results closer to the experimental flight paths.

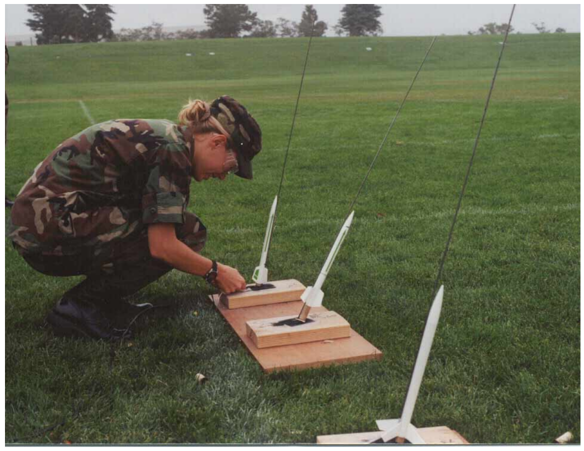

**Figure 1 – Rocket launch pads**

*Rocket Launch Results*

The rocket launch project was a very easy way to get the students involved in a hands-on project early in the course. The students rated the rocket problem highly with respect to adding interest and motivation, averaging a 3.74 on the five point Likert Scale. Comments included "the rocket was fun, but it could be nice to build stuff for other labs" and "It's hard to get motivated to learn dynamics; the rocket lab was the best attempt".

With regard to increasing student understanding of the material, the average score was 3.46. One student thought "for something as simple as projectile motion, the rocket project was excessive." Only four students opted to do the optional computational mechanics problem that included drag and thrust calculations; this will be made mandatory next semester.

## THE EFFECT OF MASS ON MOTION

Students in a first dynamic's course, even after studying Newtonian physics in both high school and college, still have a fundamental lack of understanding of the difference between mass and force (weight) and their influences on motion. The confusion may come because students first study statics where a system's acceleration is not considered and thus mass and weight seem to have equivalent effects. This misunderstanding is demonstrated through discussion and/or test problems of the type shown in Figure 2. For this figure with $M_1 > M_2$, we typically ask which system will accelerate faster. The typical student answer is that both systems will accelerate equally.

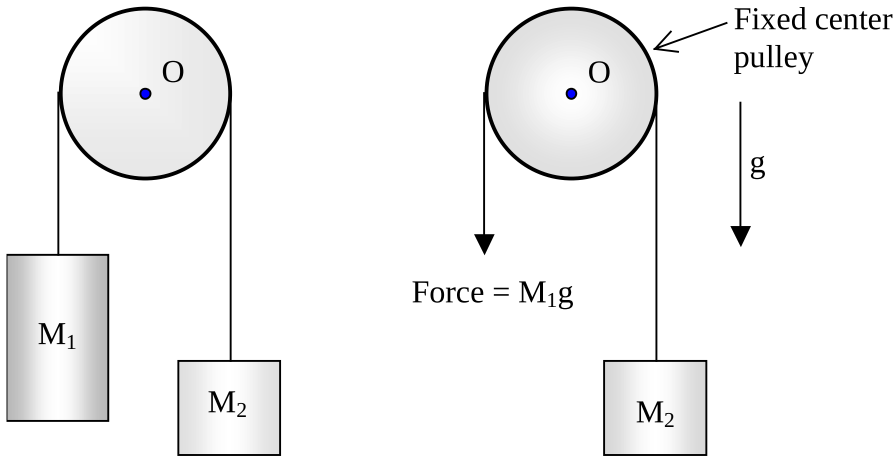


**Figure 2 – Schematic of contrasting dynamic systems**

The conceptual problem comes from the thinking that if the net forces on the system are the same, the acceleration must be the same. The idea of the mass affecting the acceleration is not so clear. This problem has been discussed many times and through many semesters, but when the concept is tested, the understanding typically has not been there.

To try to bring visualization to this concept as an aid to understanding, we built a demonstration device that mimics the Figure 2 concept. Figure 3 shows a schematic of the demonstration.

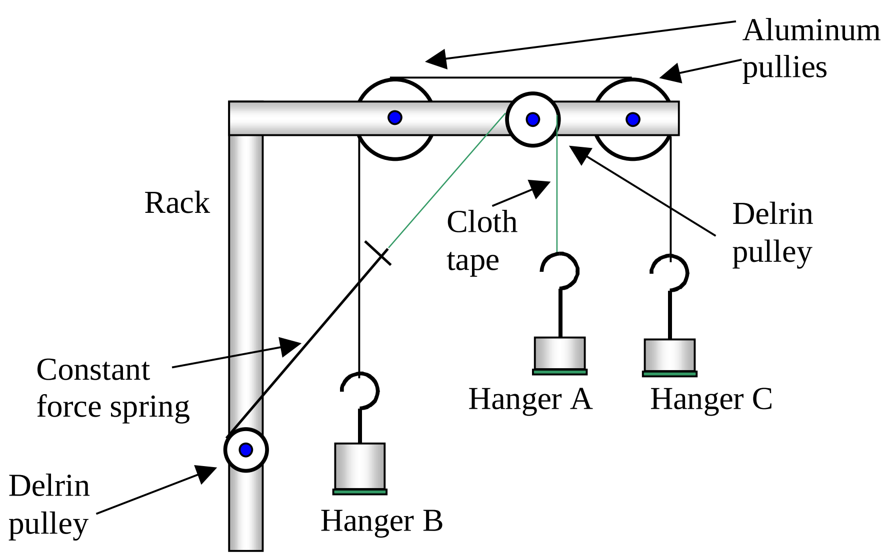


**Figure 3 – Demonstration set-up for mass-weight concept**

Two pulley systems are constructed side by side. The Hanger B-C system has added masses on each hanger. The Hanger A-constant force spring system has an added mass on Hanger A. In our case, the constant spring force and the total weight at B were both 8.0 lbs, and the total weight on A and C were both 5 lbs.

In the set-up, the spring is a tape measure type spring and can be bought from a small parts supplier. The spring is attached to a cloth tape such as a seamstress would use so that the spring never wraps over the top Delrin[1] pulley. Ball bearing pulleys are used to minimize frictional effects. Hangers B and C can be connected with a light cord. The smaller the force difference between the two sides of each system the better, but there must be enough difference to significantly overcome any frictional effects. Small force differences afford lower accelerations.

The demonstration is simple. Hangers A and C are manually lowered until the constant force spring is sufficiently extended. In our case, that was about 18 inches. Both hangers are then released simultaneously and the two mass system will be distinctly slower than the force-mass system. It is also usually necessary to catch the masses before they reach the limits of their motion.

*Results: Distinguishing between mass and weight*
The average Likert score for student interest and motivation was 2.79, while the score for aiding understanding was 2.78. Students still had a difficult time realizing that the tensions were different for the two different scenarios. This could be because what was meant as a hands-on lab became a classroom demo due to the fragility of the mechanical set-up. One problem was that the constant force spring easily became twisted. Students also were not careful with the weights and pulleys and “crashes and collisions” degraded the performance of the device. Our conjecture is that a more robust set-up would afford hands-on functionality and increased understanding.

## CATAPULT LABORATORY

A major course objective at the Academy is to enable the students to work multiple part problems (e.g., recognize that they may need to apply work-energy to determine an initial impact velocity and then conservation of angular momentum for the second part of a problem). One example of this was used in a Catapult Laboratory. A simple Statapult (Air Academy Press, Colorado Springs, CO) shown in Figure 4 was utilized for the tests; these catapults are currently used in the Mathematics Department in a statistics class, so many students will use them again. Components of the catapult, including the arm, eye-bolts, and ammo cup were weighed, and values were provided to the students. The ammunition used were raw eggs, which had masses of between 45 and 65 grams. The elastic properties of the rubber band were measured using hanging weights, and the load-displacement data were given to the students. Finally, three different initial settings/final angle combinations were provided to the student teams.

The students then had to calculate how far an egg would fly before hitting the ground. This entailed calculating the mass moment of inertia of the moving masses about the pin, calculating the potential energy in the catapult system, and then calculating the angular velocity of the arm just before it hits the stop. The second part of the problem is simply a projectile motion exercise.

The catapult was placed on a table that was 26 inches high, and the students had to place a target box at the location where they calculated the egg would land. The box gave them about two feet of leeway to account for individual egg variation and calculation errors. If the students didn’t calculate their distances correctly, their punishment was to clean up their spent ammo.

[1] Delrin is an easily machineable, solid nylon product.

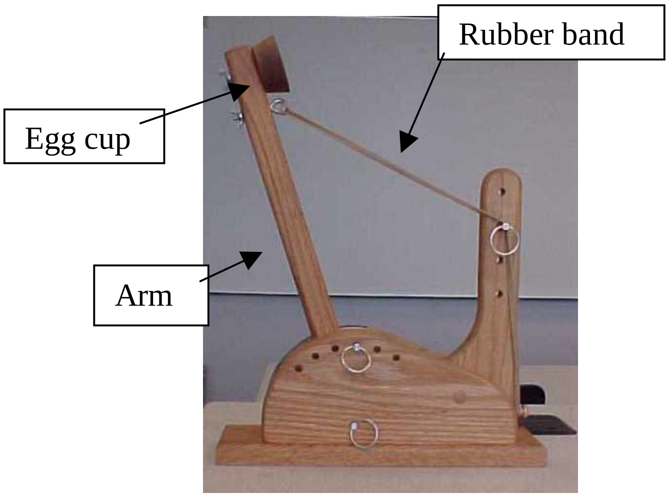


**Figure 4 - Statapult used in catapult lab.**

*Results: Catapult Laboratory*

The score for student motivation and interest for the catapult lab was 3.53. In general, the students seemed to have fun with the project and could see where work-energy could be used in a real-life situation. Comments included "catapult project was definitely the best" and "with the catapult project, we had to apply several different concepts to solve it." This comment was also reflected in the score for aiding student understanding, which was 3.48. Only a handful of students attempted to calculate the amount of stress in the hinge pin; this may be required next semester.

**CHARPY PENDULUM DEMONSTRATION**

As mentioned in the Catapult Laboratory discussion, we feel it is important for the students to be able to solve multi-part problems. To help motivate this, a simple Charpy test device present in most engineering labs was used as a demonstration (Figure 5). During class, students calculated the mass moment of inertia of the device about the pivot point and determined the angular velocity of the hammer just as it struck the test specimen. After it impacted the test specimen, the students measured the final height of the pendulum. Variables that can be calculated during the exercise include the amount of energy absorbed by different specimens and the angular impulse applied to the specimen. The demonstration is also valuable because it uses material from other engineering courses such as mechanics of materials and failure mechanisms. Only two sections completed the demonstration, so no survey questions were asked on this topic.

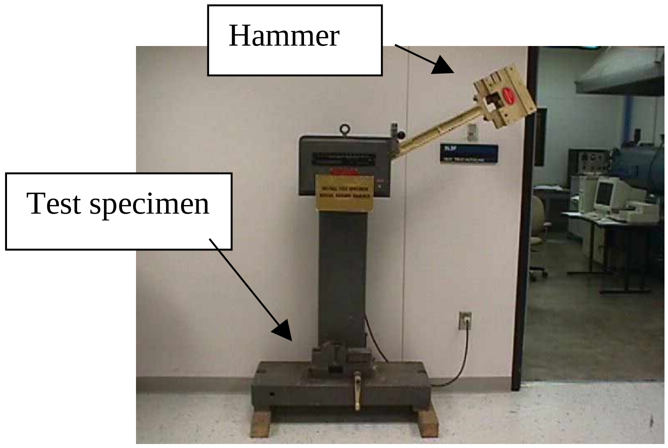


**Figure 5 – Charpy impact machine**

## SPACE HABITRAIL PROJECT

One of the most difficult concepts for undergraduates to grasp is three-dimensional kinematics. Multiple axis rotations seems to confuse the cadets, particularly when discussing obscure rods and disks that have no real life significance. Hoping to motivate the student's interest and give them a physical feel for the kinematics, we developed a space exercise project. Short-arm centrifuges have been suggested as a possible countermeasure to the ill effects of microgravity in space, such as on a space station. Utilizing this concept, we developed a project where the students were to design a circular treadmill, similar to the spinning wheels that hamsters use. The treadmill would be free to spin and could rotate about multiple axes depending on its placement on a space station. The goal of the project was to produce a reasonable amount of acceleration on the runners to give them a simulated gravitational environment.

*Results: Space Habitrail Project*

The Habitrail project ended up being too complex for the students. It was too open-ended, and the students did not have time to grasp the difficult material before the assignment was given. This is definitely reflected in the survey scores, which were 2.20 for student motivation and interest and 2.57 for understanding. Comments included "The habitrail project sucked my will to live" and "best was catapult and worst was habitrail". A similar project (probably an Air Force training centrifuge) will be used in the future, but it will not be as open-ended a problem. More guidance will also be provided to the students to aid in their understanding and performance.

## COMPUTATIONAL MECHANICS PROBLEMS

Typical of many dynamics' classes and textbooks, most of the posed problems ask for kinematic and kinetic variables at a specific point in time, rather than over periods of time. The thought may be that the dynamic concepts are new and tough enough in themselves. Why complicate the solution process by solving multiple algebraic problems or, even worse, requiring solutions to differential equations? However, in engineering, solutions are needed throughout the range of motion for mechanisms and devices to determine the limiting values of force and velocities.

Fortunately, most textbooks are now incorporating a number of computational problems that require solutions through the trajectory of a problem. With the power of calculators, spreadsheets, and programs such as Mathematica, MathCad, and others, these broader solutions are reasonable to require.

Three computational mechanics problems were assigned in the particle dynamics portion of the course. The first involved finding radial and tangential accelerations for a particle given elevation and range as a function of time. Figure 6 shows the components and magnitude that the students should have found. *Mathematica* was typically used for this.

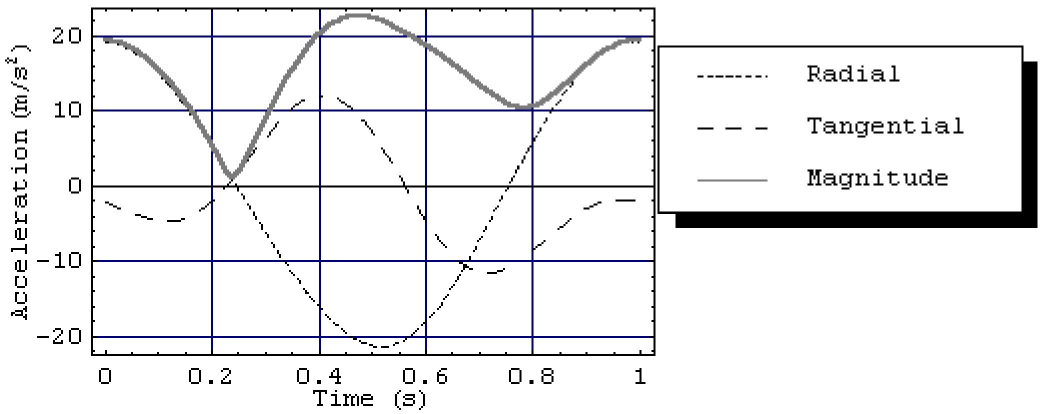


**Figure 6 – Particle tracking accelerations**

The second computational mechanics problem involved a rocket in vertical flight with the thrust given as a nonlinear function of velocity and time. The students were required to numerically integrate the acceleration to determine velocity and altitude and to compute acceleration and velocity to a given altitude of flight. Figure 7 shows these results over a period of 25 seconds. *Excel* was used for this solution to allow students to easily work with Euler integration.

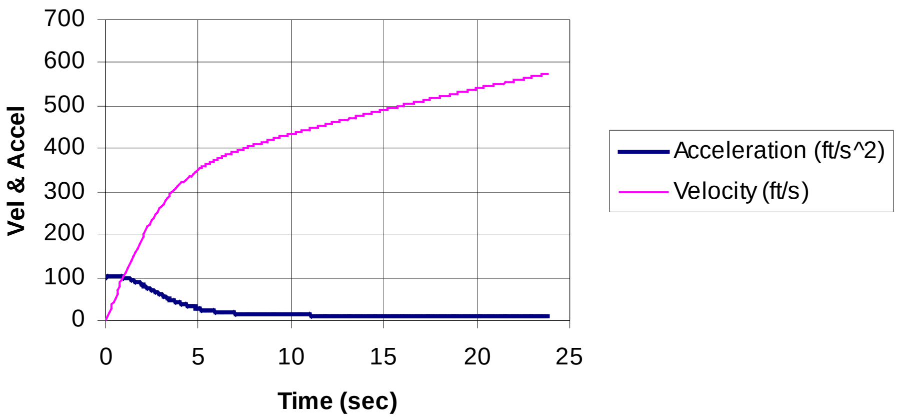


**Figure 7 – Rocket velocity and acceleration**

The third and last computational mechanics problem was finding the velocity of an object over a range of positions calculated with particle work-energy principles. Figure 8 shows a solution to this type of problem, again using *Mathematica*.

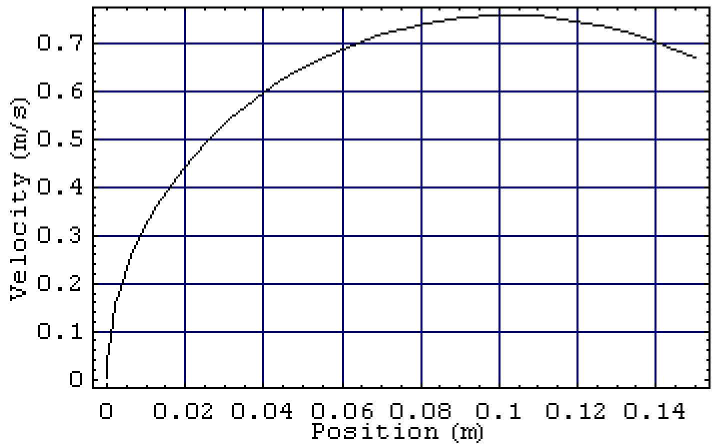


**Figure 8 – Object velocity versus position**

<u>*Results: Computational Mechanics*</u>

The motivation and interest for the computational mechanics problems was neutral, scoring 2.92. This may change next semester, when the rocket launch will be analyzed. Hopefully, the positive responses for the initial lab will carry over to the computational mechanics assignments. The understanding rating was 3.33. The projects really aided some students in realizing that dynamics problems need to be solved over a range of time and that usually our homework problems are simply solved at a defined instant in that time range. Other students had difficulty in grasping this or had weak programming and spreadsheet skills. Comments ranged from "CM's were vital to understanding the course" and "CMs instead of Homework was good" to "The CMs were ridiculously hard" and "the CM assignments just confused me."

**"REAL-LIFE" PRESENTATIONS**

To allow students to explore a little in their own interest area, short presentations were assigned to pairs of students on a real-life topic of their own choosing. The problems were to be at a level of a difficult homework problem or computational mechanics problem. The students were assigned a ten-minute slot during a regular teaching hour and presentations were done with *Powerpoint* or overheads and often with a video clip motivating the topic.

Topics were varied and usually consisted of a particle kinematics or kinetics problem. Students were to make assumptions, to formulate the problem and to present solutions. Some notable topics included: 1) examining a skier's dynamics in slalom skiing taking wind drag into account, 2) finding the impulse from expanding gasses on a shell fired from a rifle, 3) looking at the kinematics of a tennis serve, 4) studying the interaction between a gymnast and a high bar while performing "Giants," and 5) evaluating the forces during a football "goal line stand."

The topics were generally creative and the analyses were usually mostly correct. These presentations appeared to be motivational and fun for the students, and they were able to see a number of applications from other presenting pairs.

*Results: Real Life Presentations*
The real life presentations were successful in motivating the students and providing an interesting break during class. The Likert scale average rating was 3.60 for motivation and interest and 3.33 for aiding understanding. While these scores seemed a little low, the comments on the presentation were all positive. They included "I appreciated the open-ended individual presentations since I could apply dynamics to real life;" "I think doing more individual projects would increase motivation - we got to choose what we wanted to calculate;" and "individual presentations help me to learn about the material."

## OVERALL MOTIVATION AND INTEREST LEVEL

Figure 9 shows the overall interest and motivation levels for each type of assignment. It may be most useful to compare the project results to simply doing homework problems, which is traditionally done in most dynamics classes. As is evident from the graph, less than 30% of the cadets agreed or strongly agreed that the homework was interesting and motivating. All of the projects except for the Habitrail had higher percentages than this. The highest percentage of positive rating was for the rocket launch, closely followed by the catapult and individual presentations.

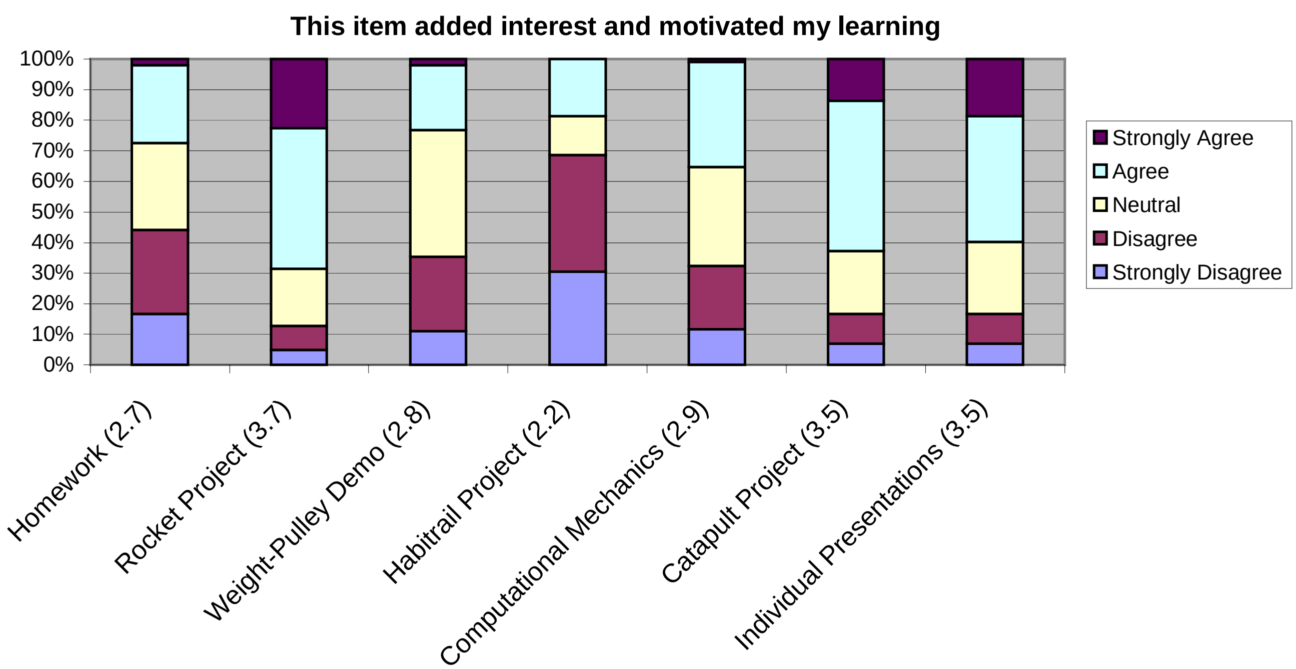


**Figure 9 - Interest and motivation levels.** Bars show percentages of responses for the students. The average scores (5= strongly agree, 1 = strongly disagree) are shown in parentheses.

Figure 10 shows how each type of assignment helped the students understand the material. As can be seen from the chart, students felt that the homework assignments were critical for them to learn the material. The catapult was the next closest score but was still nowhere near the percentages scored for the homework.

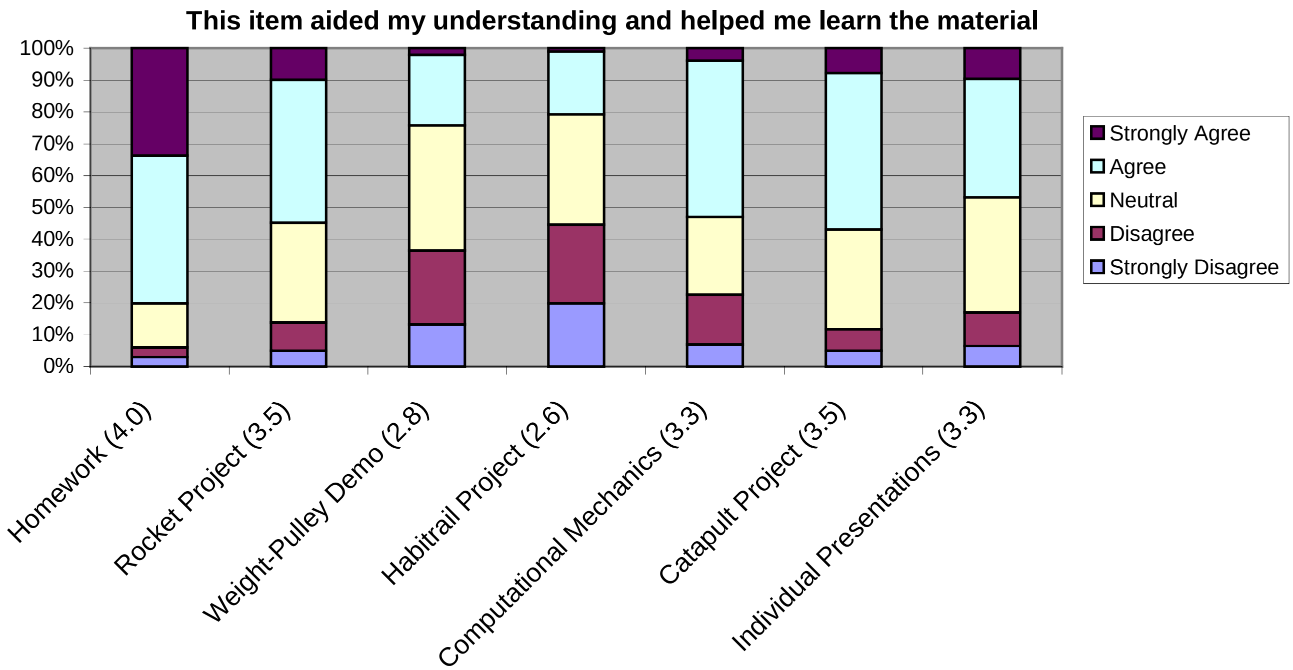


**Figure 10. Understanding and learning levels**. Bars show percentages of responses for the students. The average scores (5= strongly agree, 1 = strongly disagree) are shown in parentheses.

These results were evident in the comments that cadets made. Some examples were "homework was the most intensive, but helped the most;" "doing homework worked wonders for my grade;" "HW was useful, just too much of it;" and "the homework was enough to motivate me."

## CONCLUSIONS

Results show that the assignments that are interesting do not necessarily help the students learn the material effectively. Perhaps one student said it best: "crunching numbers helps me understand the material for what the tests require. Hands on stuff helped me understand how things are applied." Typically, homework assignments involve at least some problems that involve real world objects rather than just blocks or rods, but they still are not enough to provide high interest levels for the students. Perhaps more interesting assignments that can be worked in groups, in conjunction with smaller numbers of traditional homeworks, might prove beneficial.

Further, examining our motives as instructors might prove fruitful. Yes, we want our students to be able to do dynamics problems with some degree of competency, but we also want our students to be motivated, to see the real-life implications of what they are studying, and to take with them some long term appreciation and "big-picture" understanding of the topic. Hopefully the introduction of these labs, projects, and presentations will meet some of these objectives.