Labs: Trigonometry Based Physics Part I

To Instructors

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Summary (see following text for details):

- SOLVE is used with suggested 20% of point value awarded for successful completion of each of the 5 steps.
- Bloom's Taxonomy (modified) is used with suggested awarding 20% of point value from successful completion of each of the 5 steps.
- Graphs require correct scaling, axes labeling, and correct units. Suggested points are 20% for accurate graphing, 10% for equation of graph and/or other information (for example, slope), 10% for title, 10% for x-axis scaling, 10% for y-axis scaling, 10% for x-axis labels, 10% for y-axis labels, 10% for x-axis units, 10% for y-axis units. These guidelines may require adjustment.
- Tables require titles, equations, labels, units, and accurate calculations. Suggested points are 20% for accurate tabulation, 10% for equations, 10% for title, 10% for x-axis labels, 10% for y-axis labels, 20% for x-axis units, 20% for y-axis units. These guidelines may require adjustment.
- The influence of dimensional analysis, units conversion, unit fractions, fraction bars, and sig. figs. is on awarding points is determined by the influence on SOLVE and Bloom's Taxonomy.
- Team work and clear communication is encouraged and it is suggested reports be submitted for each lab group.
- Points are shown in the comments of reports and each report has a total of 100 points for easy grading and easy grade calculation.
- These labs comply with modern learning theory, common institutional requirements, and commonly desired outcomes to develop critical thinking, teamwork, communication, and other skills.
- Labs are generic so they are not specific equipment dependent, but develop principles. If differences in equipment are problematic, multiple versions will be written for each version of the equipment.

Introduction:

This is a sequence of 13 3-hour labs and a final lab exam suitable for a 15 week trigonometry based physics course with a pre-calculus concurrent enrollment requirement. Part I covers topics from fundamentals, kinematics (describing motion), vectors, force and Newton's laws, work and energy, linear and angular momentum and momentum conservation, circular motion, gravity and Kepler's laws, rigid body motion (rotation), torque, equilibrium, thermodynamics, solids, fluids, vibrations, and waves.

These labs are based on teaching a problem solving method (SOLVE), learning objectives *a la* Bloom's Taxonomy, error-resistant units conversion utilizing unit fractions, dimensional analysis, error detection and correction (Bloom's top level – evaluation), and keeping 3 or more significant figures (sig. figs.).

Many colleges and universities write their own labs for the main reason of lack of quality commercial labs. Compounding this is expense. This series of labs addresses both issue being of high quality incorporating recent educational theory and institutional requirements and low expense.

One aspect of these labs is an attempt to be generic regardless of equipment. For some labs, such as inclined planes, this is not very difficult. However, for example, some centripetal force equipment may utilize a spring to supply the centripetal force and another piece of equipment may use weights, etc. Separate instructions will be provided if differences between types of equipment cause large differences in instructions. It may be necessary for instructors or institutions to write one or two page operation instructions for their specific equipment. These labs are sufficiently instructional that the need for operating instructions is minimized.

Finally, due to the foundation of these labs in the most current education, teaching, and learning theory and compliance with commonly sought after assessments and outcomes, these labs have a greater chance at success in translating to internet delivery.

SOLVE Quantitative Problem Solving Method:

SOLVE[1] is a method used in Washington State K-12, and as I later discovered in popular throughout the USA, which I immediately gravitated toward when I first learned of it. While there are many sources and references to SOLVE, it is described in a visually appealing manner on Ms. Ryan's page (http://pages.cms.k12.nc.us/amyryan/solve.html)[2] and a closely related 5-Step problem solving method is published by Kinert and Abel (2006) pp. i-ii[3]. I publish my own summary at http://iws.collin.edu/jtsizemore/help/solve.htm[4] and a more detailed revision of Kinert and Abel's version at http://iws.collin.edu/jtsizemore/help/fivestep.htm[5]. The various revisions are roughly equivalent to each other and to other problem solving methods. As Arons pointed out[6], the various quantitative problem solving methods are roughly equivalent and the particular method we use is not as important as students learning a method, and using it consistently. Instructors are skilled at following well reasoned arguments, even if a quite different style than their particular style, however my experience has been that students rarely come with a well formed, well practiced method already established.

The suggested grading is to equally weight each step in the SOLVE method. For example if the student makes an accurate sketch, but accomplishes nothing else then the student would be awarded 20% of the problem's value. If the student does everything correctly and miscalculates at the very last step, the student would be awarded 80% of the problem's value. The student has accomplished 4 out of 5 steps of the SOLVE method.

The revised Kinert and Abel version (Sizemore, 2011) is reproduced below.

In Summary:

1.	**S - Sketch:**	**Sketch, draw a picture, understand the problem**
2.	**O - Organize:**	**Organize, write down known and unknown quantities**
3.	**L - List:**	**List relevant equations, determine which are applicable**
4.	**V - Vary:**	**Vary, rewrite, and transform equations to express unknown quantity in terms of known quantities**
5.	**E - Evaluate:**	**Evaluate expressions, Plug in Numbers, evaluate to determine if answer makes**

SOLVE Five Step Method In Detail:
THE FIVE STEP METHOD OF PROBLEM SOLVING

1. S - Sketch: READ THE ENTIRE PROBLEM CAREFULLY AND MAKE A SKETCH

Read through the entire problem completely before you start to write anything down. A sketch of the problem situation will help you to clarify the ideas of the problem. If you can't visualize the situation, you might be missing some important concepts.

2. O - Organize: LIST THE GIVEN INFORMATION AND IDENTIFY THE UNKNOWN QUANTITY ASKED FOR IN THE PROBLEM.

Write down each magnitude (number and units) that is given and identify it with the appropriate letter. For example, " a time of six seconds" is listed as "t = 6 sec".

It is important to use the letter symbol that will appear in the equations. For example, if a problem asks you to find "how long it takes" for an event to occur, you would write "t =?". Be sure to understand what the letter means and write it down to help you remember. For example, "t = 6 sec: t is the time it takes for the object to travel the distance."

3. L - List: LIST EQUATIONS, SELECT THE EQUATION THAT RELATES THE UNKNOWN QUANTITY TO THE GIVEN INFORMATION.

For example, if you know the velocity (v) of an object and the distance it has traveled (d), and you wish to find the time required to travel that distance (t), you would choose the equation that uses all three of these variables: $t = \frac{d}{v}$.

4. V - Vary: REVISE, REWRITE, AND TRANSFORM THE EQUATION, IF NECESSARY, TO SOLVE FOR THE UNKNOWN QUANTITY. THE REVISED EQUATION IS THE WORKING EQUATION.

The unknown (in this case, t) should appear alone on either the left or right side of the equal sign in your working equation. In the example above, if the unknown was the velocity, the equation would be rewritten to read: $v = \frac{d}{t}$.

5. E - Evaluate: SUBSTITUTE THE KNOWN INFORMATION IN THE WORKING EQUATION, INCLUDING ALL UNITS. SOLVE THE EQUATION, INDICATING THE CANCELLATION OF UNITS, AND CIRCLE YOUR ANSWER.

If you are solving for the velocity, the distance is 12 meters ("d = 12 m"), and it took 6 seconds ("t = 6 s"), then we would write (after " $v = \frac{d}{t}$ "), $v = \frac{12\,m}{6\,s} = 2\,\frac{m}{s}$. The units combine (and can cancel) just like numbers. Notice that "meters per second" is a correct unit for velocity. EVALUATE your answer to see that it has the correct units. For example, if you find that the weight of an object is in units of "square feet", then an error has occurred. Also, EVALUATE the magnitude of your answer; if it is obviously physically impossible, go back and look for an error. For example, if you find the speed of a car to be 4000 mph, the answer is not reasonable. Make sure you circle your answer to avoid confusion.

Applying Bloom's Taxonomy (units conversion & dimensional analysis):

While Bloom's Taxonomy has been around since 1956 (Bloom, 1956)[7], the version I like and relevant to college teaching is on pp. 7-8 of On Course (Lang, 2008).[8] Summarizing, the bottom is knowledge – simply regurgitating fact. Next is comprehension followed by application, analysis, synthesis, and evaluation. In quantitative disciplines evaluation means a student's ability to pull information from Chapter 1 and Chapter 14, combine it (synthesis), arrive at an answer, and evaluate and critique it for correctness. Evaluation also means the ability to review another student's work and critique it accurately and discover where the fellow student made mistakes.

Especially as Bloom's Taxonomy is applied to quantitative disciplines, application and analysis are very nearly the same. Thus I think of it as five levels rather than six and, for grading, award 20% for each level. In other words, a correct fact is worth 20% and comprehension is worth 20%. For example, comprehending the acceleration of gravity is -9.8 m/sec^2 at the peak of a ballistic trajectory. Application/analysis is worth 20%. Finding time given height for ballistic trajectories would be an example of applying physics. Synthesis is worth 20% and an example would be writing down the equation of motion of a pendulum since it synthesizes force and rigid body motion. Finally finding-and-fixing their own errors or the errors of other students (evaluation) is worth 20%. Lack of clarity in communication would be cause for reduction in points awarded per the above breakdown.

Correct units conversions employing unit fractions, dimensional analysis, and the SOLVE method assists the student in achieving the highest levels of Bloom's Taxonomy. These techniques are habits that help prevent errors. The SOLVE method was described previously and the dimensional analysis and units conversion follows.

Tables and Graphs:

Tables should precede graphs and are part of the skills a student needs to acquire for clear communication. Therefore the suggested grading for tabulation is detailed. Suggested awarding of points is 20% for accurate tabulation, 10% for equations, 10% for title, 10% for x-axis labels, 10% for y-axis labels, 20% for x-axis units, and 20% for y-axis units. Adjustments may be necessary if equations are listed elsewhere, tables have multiple columns, etc.

Accurate graphing is a portion of clear communication students need to learn. Therefore the suggested grading for graphing is detailed. Suggested awarding of point is 20% for accurate graphing, 10% for equation of graph and/or other information (for example, slope), 10% for title, 10% for x-axis scaling, 10% for y-axis scaling, 10% for x-axis labels, 10% for y-axis labels, 10% for x-axis units, and 10% for y-axis units. Adjustments may be necessary if graphs have multiple equations on the same graph, etc.

Dimensional Analysis, Units Conversion, Unit Fractions, Fraction Bars, and Sig. Figs.:

These items are discussed in detail for the benefit of students in Kinert and Abel (Kinert, 2006) pp. 4-6. I will, however, provide a short review. To convert 1 ft to meters, one would proceed as follows:

$$\mathrm{x\ (m)} = (1\ \cancel{\mathrm{ft}}) * \left(\frac{12\ \cancel{\mathrm{in}}}{\cancel{\mathrm{ft}}}\right) * \left(\frac{2.54\ \cancel{\mathrm{cm}}}{\cancel{\mathrm{in}}}\right) * \left(\frac{1\ \mathrm{m}}{100\ \cancel{\mathrm{cm}}}\right) = 0.3048\ \mathrm{m}$$

Units in the numerators cancel units in the denominators leaving only meters for the answer. The fractions in parenthesis are called unit fractions. For example, $\left(\frac{12\ \mathrm{in}}{\mathrm{ft}}\right)$ is one such unit fraction. It’s easy to show units conversions performed as shown is identical to proportional reasoning. When I introduce this I show this equivalence to prove the validity of this method to students and then go on to say that now we can use the mnemonic device of unit fractions to help use remember how to do unit conversions.

A straight fraction bar assists with this. For example an equation written: x = ½ * ¾ might look to students like x = 2*3/4 or something equally erroneous instead of the correct answer of:

$$x = \left(\frac{1}{2}\right) * \left(\frac{3}{4}\right) = \frac{1*3}{2*4} = \frac{3}{8}.$$

Using straight fraction bars helps prevent this confusion both in numerical calculation and dimension cancelation.

Dimensional analysis is best illustrated considering Newton’s second law solved for acceleration: a = F/m. A student should show dimensional analysis similar to this:

$$\text{units of a} = \frac{\mathrm{N}}{\mathrm{kg}} = \frac{\left(\frac{\mathrm{kg\ m}}{\mathrm{sec}^2}\right)}{\mathrm{kg}} = \left(\frac{\cancel{\mathrm{kg}}\ \mathrm{m}}{\mathrm{sec}^2}\right)\left(\frac{1}{\cancel{\mathrm{kg}}}\right) = \frac{\mathrm{m}}{\mathrm{sec}^2}$$

Since we arrive at the correct units for acceleration we have higher confidence in the correctness of our analysis.

Students at this level (completed trigonometry and concurrent enrollment in pre-calculus) have little understanding of error analysis and propagation. The error most students engage in is lack of precision (2 sig. figs. or less) rather than correct or excessive precision. Therefore I employ the rule-of-thumb of ALWAYS keeping 3 sig. figs. or more AND some problems may require greater precision. I’d rather the student err on the side of being overly precise rather than imprecision. I’m also clear that this is a rule-of-thumb at this stage in their learning that will be revised and nuanced in the future to more correctly handle imprecision using statistical methods.

Sometimes when students only keep 2 sig. figs., I feel like being cruel, taking away their calculator, giving them a slide rule, and saying, “Since you only do your calculations precise to 2 sig. figs., you don’t need a calculator, a slide rule will do.” Although I’m tempted to do this, I never have.

If dimensional analysis, units conversion, unit fractions, slanted fraction bars, or sig. figs. contributes to incorrect work or answers, it is suggested to deducts points per SOLVE and Bloom's Taxonomy as discussed previously.

Teamwork and SCANS (desired work competencies)**:**

Teamwork is a high priority skill we desire for our students and part of SCANS[9] (Secretary's Commission on Achieving Necessary Skills) set of desired competencies. It is, therefore, suggested labs assignments be turned in by groups rather than individuals. It is tempting to students to divide up the work, have different students do each section, and combining this. However students working alone are rarely able to earn 100% per the suggested rubric and, therefore, students will quickly learn to review the lab reports for accuracy.

While SCANS is now dated, my personal opinion is it remains valuable. SCANS competencies are resource identification, interpersonal skills, data and information skills, systems (roughly equivalent to evaluation in Bloom's Taxonomy discussed previously), and technology. SCANS foundation skills are basics (reading, writing, arithmetic, etc.), thinking, and personal qualities (responsibility, self-management, integrity, etc.).

Comparing SCANS with previous items we observe that nearly everything is covered with only a few exceptions. Even the exceptions are indirectly addressed. For example, we presume by complying with the requirements of this class that students will acquire self-management. Another example is integrity is usually covered in the academic honesty section of college policy.

Comparing the assessments described previously and desirable learning outcomes it should be clear that these labs meet nearly all desired outcomes required by educational institutions. The goal is that this "To Instructors" document provides meaningful information for the instructor to match their institution's specific learning outcomes with assessments and outcomes used in these labs.

Learning Outcomes

SOLVE, Bloom's Taxonomy, and the previous items discussed form the basis for learning outcomes for these labs. Thus, we will not reiterate the reasoning behind the following learning outcomes – we will simply present them.

Sometimes by listing content mastery we lose sight of the more general skills we desire to impart to students. Therefore, based on SOLVE, etc., we've created more general and overarching desired outcomes:

- Understand, comprehend, apply, and explain concepts
- Analyze and solve problems using Quantitative Reasoning method (SOLVE, Five Step, or equivalent)
- Synthesize knowledge to solve problems, evaluate student's own work and work of others, and find and fix student's own errors and errors of others
- Fluent and correct dimensional analysis in English and/or SI (metric) units
- Explain reasoning verbally, in writing, and other communication methods employing a scientific and/or technical writing style
- About 2 hrs study outside class for every hour in-class or lab. Struggling students will require more.
- Apply, acquire, and improve academic disciplines, study habits, and time management
- Cooperatively work together and behave ethically, civilly and responsibly including respect for property. Refrain from playing inappropriately with lab equipment which has the potential to damage it.

The official version our institution uses below expresses more of the content mastery we desire:

Upon successful completion of this course, students should be able to do the following:

1. Demonstrate knowledge of basic units of measurement and their relationships
2. Solve problems through equations involving the motion of bodies
3. Solve problems involving forces including frictional forces
4. Solve problems involving work and energy
5. Solve problems involving momentum and collisions
6. Explain the basic principles of fluid dynamics

7. Apply the principles of heat and thermodynamics
8. Explain and apply the principles of wave motion and sound
9. Demonstrate the collections, analysis, and reporting of data using the scientific method

Lab Organization:

The role of labs in physics instruction has been hotly debated for at least a century[10,11]. Both recent and older research shows discovery based (exploratory, “open ended”) learning to be slightly better[12,13,14] in helping students learn the concepts of the discipline. However this is not the sole goal of labs and, while our labs are prescriptive, they are not strictly traditional or cookbook – we sought to combine the best of traditional and discovery labs. This is not an original concept – Mayer[15] argues for it, refers to this as “guided discovery,” and his paper includes an impressive bibliography both pro and con of discovery based and traditional learning. We sought to implement such a “guided discovery” approach in writing these labs.

We retrain a more traditional approach to encourage students learning communication skills, performing clear and valid mathematical reasoning and statistical analysis, writing well-reasoned reports of their observations, and providing meaningful, clear visualization of information. We diverge from tradition in posing questions to challenge student’s preconceptions or misconceptions, requiring students to explain their reasoning before and after the lab (deduction), inquiring if results met expectations or violated expectations (induction), encouraging students to engage in a discovery process, to experiment, and to clearly communicate their reasoning.

While the authors would like a less prescriptive approach, it is believed that students at this level require this prescriptive “hand holding” before they advance into more pure discovery “open ended” labs. Furthermore we would desire that student may imitate this structure and style as a template for open ended labs or other future work.

The labs consist of prelabs, prelab quiz, the lab itself, and postlabs. The time allotted is designed for 3 hours in class with a half hour to 45 min. required for the prelab outside class. The prelab is then required at the beginning of the lab period. A problem has been observed that students do the prelab just before the lab is scheduled to begin and arrive late in the lab. To address this, a quiz is developed to test the content of the prelab and administered immediately at the beginning of class. This alleviates tardiness and lack of attention to the prelab.

No space is given for open-ended student answers in the labs. There were multiple reasons for this. (1) It was felt students need to get used to attaching separate papers to show their work, (2) if space were provide some students would not find it sufficient and attempt to (unproductively) squeeze their answers on the space allotted, and (3) it save paper printing. Since these labs are open source (please give attribution to the original authors) and with modern word processors, it is easy add student work spaces to this document as individual instructors see fit.

The lab itself is designed with instructions at the beginning and reporting near the end. There was some discussion of this – some authors preferred having instructions in line with the report and others did not. It was felt, however, that this was a minor point. Since these labs are open source (please give attribution to the original authors) and with modern word processors, it is easy to rearrange the order of presentation as an individual instructor sees fit.

The word version of assignments is provided which includes comments with suggested point values. The instructor can then print the document showing markup for themselves for use in grading and final document (sans comments) for students. The total value of each assignment is 100 points thus making grade calculation easier.

Lab answers are published here, however it may be advisable for instructors to mark up their lab copies with thorough work and notes and ascertain they come to the same conclusions.

In summary, students must do work on their own lined or graph paper and the report itself is a few pages near the end. However, by cutting and pasting and avoiding the need to change content, these documents should be quick and easy to amend to accommodate different styles.

Future Work and Online Labs:

There is a trend in education to do more and more via the internet. I recall words of wisdom I heard many years ago that applies to this: To develop a good computerized system, have good manual systems first. These labs are designed to be good, high quality, manual, face-to-face instructional labs with good outcomes and assessment. Another alternative to web-based delivery, to better fit student's schedules, are drop-in labs. We keep these trends in mind as we designed these labs. Part of the effort to design labs less dependent on specific equipment is bowing to potential web-based or drop-in delivery.

Also the rubrics specify specific point values for specific activities – again permitting better translation to the web. For example, a web-based graph might be a blank grid and a set of text boxes. The student then would click on the grid to plot their points and input text. Items like units could be instantly graded providing feedback for the student. More subjective items, like title, would be graded later by the instructor. Also a line drawing could be provided for students to create best-fit-line, but the computer could then draw a best-fit-line. It is recommended computerized programs include a robust regression[16], such as least-median-deviation, in addition to least-squares fitting since least-squares fitting is leveraged by outliers, students are more prone to make mistakes that create outliers, and robust methods are closer to what a human might perceive.

While these labs are strictly face-to-face, the solid foundation of these labs in teaching and learning theory, objective criteria, less equipment dependences, etc. will improve translation to drop-in, internet, or other forms of delivery.

Conclusion:

These labs are designed to encourage student skill building as required by modern education, educational institutions, workforce education, and employers. These skills include critical thinking, teamwork, problem solving, planning, and communication. The labs are designed to be as generic as possible accommodating a variety of lab equipment with possible minimal operation instructions required. Grading and grade calculation is expedited by providing a suggested rubric, it is easy to print student copies, instructor copies with side-by-side correspondence to student copies are provided, and the reports total 100 points each. Finally the Creative Commons license allows authors to modify these documents to meet their specific needs. These labs provide the basis for quality lab instruction in trigonometry based physics.

Solutions:

Tests, quizzes, and solutions are available to instructors only. Please contact the physics department at Collin College for this material. Be prepared to promise not to share or distribute tests, quizzes, and solutions and be prepared to provide evidence of your teacher or faculty status.

References:

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