Physics 110 Constants and Equations Sheet

Acceleration due to Gravity at Earth’s Surface  \( g = 9.81 \text{ m s}^{-2} \)

Universal Gravitation Constant  \( G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2} \)

Speed of Light in Vacuum  \( c = 3.00 \times 10^8 \text{ m s}^{-1} \)

Mass of Earth  \( M_E = 5.97 \times 10^{24} \text{ kg} \)

Radius of Earth  \( R_E = 6.37 \times 10^6 \text{ m} \)

1 in = 2.54 cm

1 mi = 1609 m

1 ft = 0.3048 m

1 mi/h = 0.447 m/s

1 lb = 4.448 N (weight) = 0.454 kg (mass)

\[
x = x_0 + v_0 t + \frac{1}{2} a t^2
\]

\[
s = \theta r
\]

\[
\theta = \theta_0 + \omega_0 t + \frac{1}{2} a t^2
\]

\[
v = v_0 + at
\]

\[
v = \omega r
\]

\[
\omega = \omega_0 + at
\]

\[
v^2 = v_0^2 + 2a(x - x_0)
\]

\[
a_t = \alpha r
\]

\[
\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)
\]

\[
a_c = \frac{v^2}{r} = \omega^2 r
\]

\[
\sum \vec{F} = \frac{d\vec{p}}{dt} = m\vec{a}
\]

\[
l = \sum mr^2 = \int r^2 dm
\]

\[
\sum \vec{t} = \frac{d\vec{L}}{dt} = l\vec{a}
\]

\[
\vec{t} = \vec{r} \times \vec{F}
\]

\[
\vec{p} = m\vec{v}
\]

\[
\vec{L} = \vec{r} \times \vec{p}
\]

\[
\vec{L} = l\vec{\omega}
\]

\[
\Delta(K + U) = W_{\text{added/removed}}
\]

\[
W = \int \vec{F} \cdot d\vec{r}
\]

\[
F_S = -kx
\]

\[
W = \int \tau d\theta
\]

\[
K = \frac{1}{2}mv^2
\]

\[
P = \frac{dW}{dt} = \vec{F} \cdot \vec{v}
\]

\[
K_{\text{rot}} = \frac{1}{2}I\omega^2
\]

\[
\Delta U = -\int \vec{F} \cdot d\vec{r}
\]

\[
U_g = mgh
\]

\[
U_s = \frac{1}{2}kx^2
\]

\[
U_c(r) = -\frac{GMm}{r}
\]

\[
F = \frac{Gm_1m_2}{r^2}
\]

\[
\omega = \sqrt{\frac{k}{m}}
\]

\[
\omega = \sqrt{\frac{g}{L}}
\]
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Course Description and Policies

Overview

The US Air Force Academy offers a broad general physics curriculum with four specialized physics major options: Astronomy, Laser Physics/Optics, Space Physics, and Applied Physics topics such as nuclear physics. Each physics major option requires 42 credit hours of physics and mathematics courses in addition to core academic requirements, including a faculty-directed capstone physics research project. After graduation physics majors succeed in a wide variety of operational Air Force assignments or complete an advanced academic degree at graduate school.

The USAFA Department of Physics offers two core courses, each with an honors option. PHYSICS 110/110H (General Physics I) is the first in a two-part series of introductory calculus-based physics courses, which includes Newtonian mechanics and conservation of energy and momentum, and is normally taken during the fourth-class year. PHYSICS 215/215H (General Physics II) is the second in the series of introductory calculus-based physics courses which emphasizes electromagnetism and circuits, and is normally taken during the third-class year.

Honors physics courses are designed to better address the needs of technical majors at the US Air Force Academy and meet the needs of an increasingly technical Air Force. Cadets demonstrating aptitude in calculus or having previously taken introductory physics courses may be placed in honors physics. Honors physics includes enhanced coverage of the concepts covered in the regular course, with more integrated use of calculus, introduction to differential equations and rigorous data analysis techniques.

Core Physics Course Descriptions

Physics 110, General Physics I, is a calculus-based introduction to classical physics, with emphasis on contemporary applications, in which you will learn the concepts and problem-solving skills required to understand and analyze the motion of objects. The first half of the course is a solid foundation in kinematics and Newton's laws of motion. You will then be introduced to several conservation principles, which are elegant ways of visualizing and understanding the motion of objects. These include the conservation of energy, momentum and angular momentum. Along the way, you will be introduced to a few topics that are important to scientists and engineers, including orbital motion, rotational motion and oscillations. Labs and simulations highlight key physics concepts.

Physics 215, General Physics II, is an introductory calculus-based physics course with an emphasis on contemporary applications. The course begins with a foundation in the basic properties of electric charge and works up to dealing with the sophisticated concept of the electric field. Then, simple circuits are analyzed, relating the principles of potential energy and electric potential to the electric field. Next, magnetic fields and electromagnetic induction are studied, culminating in a complete description of electromagnetic fields. After that, light waves, the bending of light and the
interference caused by the wave nature of light are studied. Finally, modern physics is introduced by studying quantization and quantum uncertainty. This course utilizes vectors and calculus in problem solving and includes in-class laboratories to highlight key concepts.

**Honors Core Physics Courses**

As a “techie” major in the Physics Honors Course sequence, you can expect a number of benefits compared to taking the standard introductory course. Perhaps the most significant benefit is learning physics more efficiently and more enjoyably amid students of similar academic abilities. You will also see enhanced coverage of topics that are important for scientists and engineers, including

- a more integrated use of calculus throughout the course
- an introduction to the use of differential equations in simple harmonic motion
- enhanced data analysis techniques
- somewhat more emphasis on graphical and numerical techniques

The emphasis on these topics will make your physics experience comparable to what your peers would receive at a civilian university when taking a physics course for scientists and engineers.

To allay possible concerns about your grade, DFP will ensure that you are not penalized for taking Physics Honors in place of standard Physics Course. The graded reviews for Physics “regular” and Physics Honors will include a large percentage of common questions to allow a good statistical comparison of the two courses, so that your final grade will not depend on which version of the course you take. We have also balanced the overall workload so that students in either course, on average, have the same number of homework problems, journal questions, etc., to complete.

**What are the similarities and differences between Physics “regular” and Physics Honors?**

Both courses will follow the same basic syllabus and use the same course policies. With few exceptions, students in both courses will study the same textbook examples and answer the same journal and preflight questions. Some (about 35%) of the homework problems are different to make better use of calculus and other math skills or to highlight different physics concepts. About half of the scheduled labs are common between the two courses. The other labs will be more open-ended for Honors than for the standard course and will require a short 1-2 page written report. To balance the workload, Honors students will be excused from the lab quizzes for these three labs as well as all of the computer simulation exercises in Physics 110. The graded reviews will be very similar; about two-thirds of each GR will be questions and problems common to both courses. Finally, class time will be used a bit differently in Honors, with less time devoted to covering the most basic material.

**Core Physics Course Prerequisites**

For a student enrolled in Physics 110, he or she must have completed or be enrolled in in Math 142. Important math concepts required:

Course Description and Policies

✓ Algebra and trigonometry
✓ Vector operations including dot product and cross product
✓ Differentiation of polynomials and simple functions
✓ Integration of polynomials and simple functions

Students in Physics 215 must have completed Physics 110 and Math 142.

USAFA and Core Physics Course Outcomes

Physics core courses (Physics 110 and Physics 215) are a primary contributor to the development and assessment of the following USAFA outcomes: quantitative literacy, critical thinking and principles of science, and the scientific method. Additionally, these courses are designed for you to:

1. Develop a deeper, more integrated understanding of physical concepts, with a focus on the concepts of motion, Newton’s Laws, energy, momentum, electricity, magnetism, and selected topics in modern physics.
2. Apply thinking and problem-solving skills to make informed conclusions about the meaning of physical data and information.
3. Apply experimental skills and reading comprehension to investigate principles of nature.
4. Cultivate habits of the mind consistent with that of an educated, scientifically literate person.

Core Physics Learning Goals

Physics 110 is designed to enhance your critical thinking skills and your ability to:

1. Describe the motion of objects using kinematics
2. Interpret and solve motion problems using Newton’s three laws
3. Analyze the motion of objects using conservation of energy, momentum and angular momentum
4. Develop valid physics-based conclusions about real-world problems and applications

The course learning goals for Physics 215 are:

1. Identify how the fundamental physical principles of electricity, magnetism apply to conceptual or quantitative problems.
2. Solve conceptual or quantitative physical problems involving electricity, magnetism and modern physics.
3. Apply experimental skills to investigate the physical principles governing electricity and magnetism.
4. Analyze and explain the physical principles that apply to the operation of electro-magnetic systems and circuits.
Physics Core Course Administration

<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
<th>Office</th>
<th>Phone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics Department Head</td>
<td>Col Kiziah</td>
<td>2A33</td>
<td>333-3510</td>
</tr>
<tr>
<td>Director of Core Programs</td>
<td>Lt Col Novotny</td>
<td>2A27</td>
<td>333-9248</td>
</tr>
<tr>
<td>Physics 110 Course Director</td>
<td>Lt Col Kayser-Cook</td>
<td>2A43</td>
<td>333-0357</td>
</tr>
<tr>
<td>Assistant 110 Course Dir</td>
<td>Capt Sorensen</td>
<td>2A101</td>
<td>333-9733</td>
</tr>
<tr>
<td>Physics 110H Course Director</td>
<td>Dr. de La Harpe</td>
<td>2A219</td>
<td>333-9719</td>
</tr>
<tr>
<td>Assistant 110H Course Dir</td>
<td>Maj Buchanan</td>
<td>2A109</td>
<td>333-7707</td>
</tr>
<tr>
<td>Physics 215 Course Director</td>
<td>Maj Lane</td>
<td>2A153</td>
<td>333-3615</td>
</tr>
<tr>
<td>Assistant 215 Course Dir</td>
<td>Mrs. Lickiss</td>
<td>2A149</td>
<td>333-3412</td>
</tr>
<tr>
<td>Physics 215H Course Director</td>
<td>Dr. Kontur</td>
<td>2A107</td>
<td>333-4224</td>
</tr>
<tr>
<td>Assistant 215H Course Dir</td>
<td>Lt Col Anthony Dills</td>
<td>2A25</td>
<td>333-3272</td>
</tr>
</tbody>
</table>

Your Physics Instructor ➔

Required Course Materials

The following materials are required for this course and must be in your possession on Lesson 1. Failure to possess your personal copy of each of the following is a failure to meet course requirements. Questions may be directed to the Director of Core Programs or the Physics Department Head. In addition to the first day of class, you are required to bring the following to each class period: your textbook and your entire Journal (in a 3-ring binder).

Physics 110 and Physics 110 Honors:

- **JOURNAL.** The *Physics 110 Journal* contains course guidance, syllabus, learning objectives, questions, and problems.
- **MASTERINGPHYSICS.** MasteringPhysics® is the online homework system that accompanies the textbook. An account can be purchased with the textbook or separately, but is required for the course. To purchase MasteringPhysics® separately, go to [www.masteringphysics.com](http://www.masteringphysics.com), in the REGISTER block click on the STUDENTS button and follow the instructions. Leave Student ID blank. The Course ID is listed in the following table:

<table>
<thead>
<tr>
<th>Course</th>
<th>Mastering Physics Course ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 110</td>
<td>FALL2013PHYSICS110</td>
</tr>
<tr>
<td>Physics 110H</td>
<td>FALL2013PHYSICS110H</td>
</tr>
</tbody>
</table>
• **SUPPLEMENTAL COURSE MATERIAL.** All other course material is available on the Physics 110 SharePoint sites:

<table>
<thead>
<tr>
<th>Course</th>
<th>Sharepoint Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 110</td>
<td><a href="https://eis.usafa.edu/academics/physics/110/default.aspx">https://eis.usafa.edu/academics/physics/110/default.aspx</a></td>
</tr>
</tbody>
</table>

Physics 215 and Physics 215 Honors:


• **JOURNAL.** The *Physics 215 Journal* contains course guidance, syllabus, learning objectives, questions, and problems.

• **MASTERINGPHYSICS.** *MasteringPhysics®* is the online homework system that accompanies the textbook. An account can be purchased with the textbook or separately, but is required for the course. To purchase *MasteringPhysics®* separately, go to [www.masteringphysics.com](http://www.masteringphysics.com), in the REGISTER block click on the STUDENTS button and follow the instructions. Leave Student ID blank. The Course ID is listed in the following table:

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<th>Mastering Physics Course ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 215</td>
<td>FALL2013PHYSICS215</td>
</tr>
<tr>
<td>Physics 215H</td>
<td>FALL2013PHYSICS215H</td>
</tr>
</tbody>
</table>

• **SUPPLEMENTAL COURSE MATERIAL.** All other course material is available on the Physics 215 SharePoint sites:

<table>
<thead>
<tr>
<th>Course</th>
<th>Sharepoint Sites</th>
</tr>
</thead>
</table>

**Course Policies**

**WORKED EXAMPLES** – Core Physics uses the *Worked Examples* approach to learning, which requires students to come to class prepared to discuss lesson material. For this reason, class preparation points are heavily weighted (18-20%) and include journal questions, pre-class problems, and preflight questions.

**JOURNAL QUESTIONS** – *Journal questions* are assigned for all lessons, excepted as noted on each lesson page in your journal. Read the selection from the textbook, study the assigned examples, and answer the questions based on those examples. Give complete answers and justify as you would on an exam-prep quiz or graded review. Your instructor will grade your Journal each lesson to assess your level of preparation for class. The goal of this assessment is to evaluate your honest,
thoughtful effort at reasoning through the problems. If you get stuck on a problem, review the example problems in the chapter and note how the concepts and equations in the section are applied. If you are still stuck, you can receive credit for your Journal by writing down as much of the solution as you are able, listing specific questions you have and identifying points of confusion. Journals will be graded based on the following guidelines:

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/3</td>
<td>Good effort was made to answer all Journal Questions. Good effort was made to solve the Pre-Class Problem(s) in a logical format (IDEA format is recommended).</td>
</tr>
<tr>
<td>2/3</td>
<td>One or two Journal Questions were not answered or poor effort was made to answer several of the Journal Questions. Poor effort was made to solve the Pre-Class Problem(s) or a logical approach was not used.</td>
</tr>
<tr>
<td>1/3</td>
<td>Multiple Journal Questions were not answered or the Pre-Class Problem was mostly or entirely unfinished.</td>
</tr>
<tr>
<td>0/3</td>
<td>Less than 50% of the Journal Questions for the lesson were completed.</td>
</tr>
</tbody>
</table>

If you are more than 15 minutes late unexcused, you will receive a zero for the Journal grade.

**PREFLIGHT QUESTIONS** – Preflight questions are assigned each lesson except graded review lessons. Preflights are intended to be done after the journal questions. Preflight questions must be submitted online no later than 0700 before the start of each lesson. They are designed to assess your understanding of the lesson material and provide feedback to your instructor before class. Answer the preflights in your Journal then enter your responses in the Just-In-Time Teaching (JiTT) application at [http://dfp-usafas-computer.usafa.edu/usafa/login.php](http://dfp-usafas-computer.usafa.edu/usafa/login.php). Your user name is based on your e-mail account, e.g. C14Joe.Smith, and the default password is fall2013. Responses are graded through the JiTT application. Your instructor will not grade written preflight responses in the Journal.

**PRE-CLASS PROBLEMS** and **HOMEWORK PROBLEMS** – Pre-class problems are selected from the textbook or uniquely designed for the lesson. Pre-class problems are graded as part of each lesson’s Journal grade. Pre-class problems are chosen to give you practice developing essential skills to understand the lesson.

**HOMEWORK PROBLEMS** – Homework should be completed in your Journal to provide you reference and study material for class, quizzes, and exams. (Some quizzes may be “open Journal!”) Once the homework problems are completed, you should enter your answer into Mastering Physics to be scored.

**LABS** and **LAB QUIZZES** – On lab days, you will complete the data collection and analyses as a group, hand in the lab worksheet as a group, and then take an individual-effort lab quiz. If you are more than 15 minutes late unexcused, you will receive a zero for the lab worksheet. You may
participate with a lab group and take the lab quiz. For excused absences, you must complete missed labs within 3 lessons (6 class days). Exemptions to this policy must be approved by the Course Director. Lab worksheets are available on the Course’s SharePoint site. Additional instructions are on individual lesson pages within the Journal. The Honors Courses may be required to complete a lab report which is further defined in Appendix A.

EXAM-PREP QUIZZES – Exam-prep quizzes (EPQ) consist of workout and multiple-choice problems similar to those on graded reviews and the final exam. You should use these quizzes to gauge your understanding of the material before the exams. Additional resources may be used depending upon course director policy and will be announced prior to the EPQ.

GRADED REVIEW ADMINISTRATION – Graded Reviews (GRs) normally consist of ten multiple-choice questions, and several workout problems. You will have 80 minutes to complete the exam.

   GRADING – Physics is not a “plug-and-chug” subject. Submitting a numerically correct answer for a workout problem does not guarantee credit. It is possible to get the right number with the wrong physics. Your score is determined by the soundness of the reasoning that led to your answer. In order to receive full credit you must identify the main physics concepts and show each step in the problem-solving process (IDEA format is recommended).

   ABSENCE and TARDINESS –

   (a) If you will be absent during a Graded Review due to a USAFA Scheduling Committee Action (SCA), you are responsible to notify your instructor at least THREE DAYS (not including weekends) PRIOR to the first offering of the exam. If you are more than 15 minutes late unexcused for a Graded Review, you must take a makeup exam with a 25% penalty. If you are less than 15 minutes late, you may still take the exam during the scheduled time.

   (b) If you will miss a lesson for any reason, complete and turn in a copy of that lesson’s graded work before you leave or send it with another student to turn in on time.

   MAKEUP EXAMS (GRs and Quizzes)– If you are traveling with an athletic team or cadet club, the preferred option is to take the exam on the road. If this is not an option or if you have missed the exam for another reason, work with your instructor to schedule a time to make up the exam within two lessons.

   FINAL EXAM and VALIDATION – The Final Exam is a comprehensive examination including material from the entire course. The final exam is your opportunity to demonstrate proficiency; therefore, validation of the Final Exam is not offered.

   DOCUMENTATION – Clearly document all help received on graded work from sources other than your Wolfson textbook. Please feel free to seek help from other instructors, students, or other texts at any time. For all graded work outside of class, you may use the following AUTHORIZED RESOURCES: Any published or unpublished source, web sites, and any individuals. For all
assignments, you must properly document all assistance and sources used according to the Physics Department policy letter on documentation standards (located on the SharePoint site). **This does not allow you to simply copy resource material or the work of another student, past or present, and document the source. There is no academic credit for copied work.** You must also indicate whether no help was received. Documentation for all outside-of-class work—is accomplished in the footer on each page of the Journal.

**ACADEMIC SECURITY** – All exam-prep quizzes and graded reviews remain under academic security until released by the Course Director. **DO NOT** discuss the contents or the difficulty of the material with anyone except your instructor until after it is released from academic security.

**CONSTANTS AND EQUATIONS SHEET** – You will be given a standardized Constants and Equations Sheet for use on all lab quizzes, exam-prep quizzes, graded reviews, and the final exam. Understanding the physical concepts governing the universe will not come from scanning an equation sheet in search of variables that fit the problem. You must fully comprehend the nature of the equations, the meanings of the variables, and the constraints for using each equation.

**EXTRA INSTRUCTION** – The second hour of class for most lessons is dedicated to Extra Instruction (EI). Your instructor will not cover new material or hold review sessions during this time, but he or she is available to help you. If you have other periods free, you may seek EI in any of the Physics classrooms during second hour from any instructor that is teaching your course. **Do not expect one-on-one EI if you do not seek EI during the second hour of your class.**

**RE-GRADES** – Re-grading of quizzes and labs is considered on an individual basis by your instructor. If you desire a re-grade on a graded review, first show your instructor your work and he or she will let you know if a re-grade is warranted. If it is warranted, type a Memo for Record* (MFR) explaining your case, attach it to your exam, and submit it to your instructor. The Course Director will re-grade your work. You could also **lose** points, since the entire problem will be re-graded. You have seven calendar days from the date a graded event is returned to request a re-grade.

*A Memorandum for Record is the Air Force standard for official written communications and the format is provided in the Tongue and Quill, available on the [Air Force E-Publishing website](http://www.airforcepublishing.com).
**Physics 110 Honors Course Point Structure**

<table>
<thead>
<tr>
<th>Graded Event</th>
<th>No. of Events/Points</th>
<th>Points</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Journal Questions</td>
<td>28 @ 3 points each</td>
<td>84</td>
<td>5.6%</td>
</tr>
<tr>
<td>Preflight Questions</td>
<td>30 @ 5 points each</td>
<td>150</td>
<td>10.0%</td>
</tr>
<tr>
<td>Pre-Lab Questions</td>
<td>6 @ 5 points each</td>
<td>30</td>
<td>2.0%</td>
</tr>
<tr>
<td>Lab Worksheet</td>
<td>3 @ 10 points each</td>
<td>30</td>
<td>2.0%</td>
</tr>
<tr>
<td>Lab Quizzes</td>
<td>3 @ 10 points each</td>
<td>30</td>
<td>2.0%</td>
</tr>
<tr>
<td>Lab Reports</td>
<td>3 @ 25 points each</td>
<td>75</td>
<td>5.0%</td>
</tr>
<tr>
<td>Exam-Prep Quizzes</td>
<td>4 @ 30 points each</td>
<td>120</td>
<td>8.0%</td>
</tr>
<tr>
<td>Critical Thinking</td>
<td>3 @ 15 points each</td>
<td>45</td>
<td>3.0%</td>
</tr>
<tr>
<td>Exercise</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homework</td>
<td>37 @ 3 points each</td>
<td>111</td>
<td>7.4%</td>
</tr>
<tr>
<td>Graded Reviews</td>
<td>3 @ 150 points each</td>
<td>450</td>
<td>30.0%</td>
</tr>
<tr>
<td>Final Exam</td>
<td>1 @ 375 points</td>
<td>375</td>
<td>25.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>1500</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

**NOTE 1:** Approximately 70% of the course points are individual effort (lab quizzes, exam-prep quizzes, graded reviews and the final exam).

**NOTE 2:** A sufficiently low grade on the final exam could result in failure of the course regardless of the overall score, at the discretion of the Physics Department Head.
IDEA Problem-Solving Strategy

Solving Problems Using the IDEA Format

Physics problems can be challenging, but underlying all of physics is only a handful of basic principles. If you really understand those, you can apply them in a wide variety of situations. If you approach physics as a hodgepodge of unrelated laws and equations, you'll miss the point and make things difficult. But if you look for the basic principles and for connections among seemingly unrelated phenomena, then you'll discover the underlying simplicity that reflects the scope and power of physics.

A systematic solution method helps develop critical thinking and scientific method principles. One such approach is the IDEA problem-solving strategy. Solving a quantitative physics problem always starts with basic principles or concepts and ends with a precise answer expressed as either a numerical quantity or an algebraic expression. The path from principle to answer follows four simple steps—steps that make up a comprehensive strategy for organizing your thoughts, clarifying your conceptual understanding, developing and executing plans for solving problems, and assessing your answers.

<table>
<thead>
<tr>
<th>Interpret</th>
<th>Identify the main physics concept used to solve the problem.</th>
</tr>
</thead>
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<tr>
<td>Develop</td>
<td>Draw a diagram depicting the situation. Label the given information and identify the information for which you are solving.</td>
</tr>
<tr>
<td>Evaluate</td>
<td>Solve the problem from basic principles using equations related to the main physics concepts. When possible, express the solution symbolically before substituting values into the equations. Include units with all numerical values.</td>
</tr>
<tr>
<td>Assess</td>
<td>Critically assess the validity of the solution by answering questions similar to the following:</td>
</tr>
<tr>
<td></td>
<td>a) How does the solution compare to known values?</td>
</tr>
<tr>
<td></td>
<td>b) How would the answer change if the value of one of the variables changed?</td>
</tr>
<tr>
<td></td>
<td>c) Is the solution physically possible? Explain</td>
</tr>
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“Even for the physicist the description in plain language will be a criterion of the degree of understanding that has been reached.”

Werner Heisenberg, Physics and Philosophy
Learning Objectives

Block I – Motion

During this block we will start with studying the basic concepts of displacement, velocity and acceleration. We will then use the equations of motion to analyze the motion of objects.

[Obj 1] Convert physical measurements from various units to the standard SI units of meters, kilograms, and seconds.

[Obj 2] Express quantities using scientific notation and perform addition, subtraction, multiplication, division, and exponentiation on them.

[Obj 3] Identify the number of significant figures given in a problem statement, and express the answer using the correct number of significant figures.

[Obj 4] Explain the relations between position, displacement, speed, velocity, and acceleration for an object moving in one and two dimensions.

[Obj 5] Construct and interpret graphs of position, velocity, and acceleration for an object moving in one and two dimensions.

[Obj 6] Explain the difference between instantaneous and average velocity, and between instantaneous and average acceleration.

[Obj 7] Use mathematical and graphical methods to calculate instantaneous and average velocity and instantaneous and average acceleration in one and two dimensions.

[Obj 8] Use equations of motion to solve problems involving motion with constant acceleration.

[Obj 9] Use calculus to solve problems involving motion with non-constant acceleration.

[Obj 10] Solve problems involving free-fall motion with constant gravitational acceleration.

[Obj 11] Express vectors both in component form and in magnitude - direction form.

[Obj 12] Use mathematical and graphical methods to perform vector addition, vector subtraction, and scalar multiplication.

[Obj 13] Use vectors to represent position, velocity, and acceleration.

[Obj 14] Describe how the effects of acceleration depend upon the direction of the acceleration vector relative to the velocity vector.

[Obj 15] Solve problems involving projectile motion under constant gravitational acceleration.

[Obj 16] Explain why uniform circular motion involves acceleration.

[Obj 17] Solve problems involving uniform and nonuniform circular motion.
Block II – Newton’s Laws

In this block, we start by introducing Newton’s three laws of motions. We will then use these laws to understand the concept of force, to describe different types of forces, and to analyze the motion of objects in one and two dimensions.

[Obj 18] Explain the concept of force and how forces cause change in motion.

[Obj 19] State Newton’s three laws of motion and give examples illustrating each law.

[Obj 20] Explain the difference between mass and weight.

[Obj 21] Construct free-body diagrams using vectors to represent individual forces acting on an object, and evaluate the net force using vector addition.

[Obj 22] Use Newton’s laws of motion to solve problems involving multiple forces acting on a single object.

[Obj 23] Use Newton’s laws of motion to solve problems involving multiple objects.

[Obj 24] Differentiate between the forces of static and kinetic friction and solve problems involving both types of friction.


[Obj 26] Explain the physics concept of work.

[Obj 27] Evaluate the work done by constant forces and by forces that vary with position.
Block III – Energy and Momentum

We will start this block by introducing the concepts of energy and work. Using our understanding of these concepts, we will develop the principle of conservation of energy which will allow us to analyze the complex motion of objects including those in orbits. We will finish this block discussing collisions and another conservation principle: conservation of linear momentum.

[Obj 28] Explain the concept of kinetic energy and its relation to work.
[Obj 29] Explain the relation between energy and power.
[Obj 30] Explain the differences between conservative and nonconservative forces.
[Obj 31] Evaluate the work done by both conservative and nonconservative forces.
[Obj 32] Explain the concept of potential energy.
[Obj 33] Evaluate the potential energy associated with a conservative force.
[Obj 34] Solve problems by applying the work-energy theorem, conservation of mechanical energy, or conservation of energy.
[Obj 35] Describe the relation between force and potential energy using potential-energy curves.
[Obj 36] Explain the concept of universal gravitation.
[Obj 37] Solve problems involving the gravitational force between two objects.
[Obj 38] Determine the speed, acceleration, and period of an object in circular orbit.
[Obj 39] Solve problems involving changes in gravitational potential energy over large distances.
[Obj 40] Use the concept of mechanical energy to explain open and closed orbits and escape speed.
[Obj 41] Use conservation of mechanical energy to solve problems involving orbital motion.
[Obj 42] Calculate the center of mass for systems of discrete particles and for continuous mass distributions.
[Obj 43] Explain the concept of linear momentum of a system of particles and express Newton’s second law of motion in terms of the linear momentum of the system.
[Obj 44] Explain the law of conservation of linear momentum and the condition under which it applies.
[Obj 45] Explain the concept of impulse and its relation to force.
[Obj 46] Apply conservation of linear momentum to solve problems involving systems of particles.
[Obj 47] Explain the differences between elastic, inelastic, and totally inelastic collisions.
[Obj 48] Apply appropriate conservation laws to solve problems involving collisions in one- and two-dimensions.
Block IV – Rotational Motion and Simple Harmonic Motion

During this block we will study the rotational and oscillatory motion of objects. We will start by exploring the rotation motion of rigid objects – discussing concepts of angular displacement, velocity, and acceleration. We will then revisit the concepts of Newton's Second Law, conservation of energy, and conservation of momentum as applied to objects undergoing rotational motion. We will end the course by introducing the concept of simple harmonic motion.

[Obj 49] Explain the relation between the rotational motion concepts of angular displacement, angular velocity, and angular acceleration.

[Obj 50] Use equations of motion for constant angular acceleration to solve problems involving angular displacement, angular velocity, and angular acceleration.

[Obj 51] Use calculus to solve problems involving motion with non-constant angular acceleration.

[Obj 52] Explain the concept of torque and how torques cause change in rotational motion.

[Obj 53] Given forces acting on a rigid object, determine the net torque vector on the object.

[Obj 54] Determine the rotational inertia for a system of discrete particles, rigid objects, or a combination of both.

[Obj 55] Compare and contrast the concepts of mass and rotational inertia.

[Obj 56] Use Newton's second law and its rotational analog to solve problems involving translational motion, rotational motion, or both.

[Obj 57] Solve problems involving rotational kinetic energy and explain its relation to torque and work.

[Obj 58] Explain the relation between linear and angular speed in rolling motion.

[Obj 59] Use conservation of energy to solve problems involving rotating or rolling motion.

[Obj 60] Determine the directions of the angular displacement, angular velocity and angular acceleration vectors for a rotating object.

[Obj 61] Determine the angular momentum vector for discrete particles and rotating rigid objects.

[Obj 62] Apply conservation of angular momentum to solve problems involving rotating systems changing rotational inertias and rotating systems involving totally inelastic collisions.

[Obj 63] Define simple harmonic motion and explain why it is so prevalent in the physical world.

[Obj 64] Determine the period and frequency of a simple harmonic oscillator from its physical parameters, and completely specify its equation of motion.

[Obj 65] Determine the velocity and acceleration of a simple harmonic oscillator from its equation of motion.

[Obj 66] Determine the potential and kinetic energies of a simple harmonic oscillator at any point in its motion, and describe the time dependence of these energies.
Lesson 1

Introduction

- There is a non-graded PHYSICS KNOWLEDGE ASSESSMENT TEST this lesson.

Learning Objectives

[Obj 1] Convert physical measurements from various units to the standard SI units of meters, kilograms, and seconds.

[Obj 2] Express quantities using scientific notation and perform addition, subtraction, multiplication, division, and exponentiation on them.

[Obj 3] Identify the number of significant figures given in a problem statement, and express the answer using the correct number of significant figures.

[Obj 4] Explain the relationship between position, displacement, speed, velocity, and acceleration for an object moving in one and two dimensions.

[Obj 5] Construct and interpret graphs of position, velocity, and acceleration for an object moving in one and two dimensions.

[Obj 6] Explain the difference between instantaneous and average velocity, and between instantaneous and average acceleration.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

At liftoff, the acceleration of a space shuttle is 29 m/s², and its position as a function of time is defined as \( x = at^2 \), where \( a \) is the acceleration and \( t \) is time.  

a) What is the (instantaneous) velocity \( v \) of the space shuttle one second after liftoff?  
b) What is the average velocity \( \bar{v} \) over the first minute after liftoff?

STRATEGY

We interpret this as a problem involving the relationship between position, velocity, and acceleration. Additionally, we are interested in the difference between instantaneous velocity and average velocity.

IMPLEMENTATION

We are given the position equation, so in order to arrive at a value for velocity at one given instant, we will need to take the derivative of the equation with respect to time \( (v = \frac{dx}{dt}) \). To find the average velocity, we calculate the change in position over a given length of time \( (\bar{v} = \frac{\Delta x}{\Delta t}) \).

CALCULATION

a) Velocity 1 second after liftoff (\( t = 1 \) s):

\[
v = \frac{dx}{dt} = \frac{d(at^2)}{dt} = 2at
\]

\[
v = 2(29 \text{ m/s}^2)(1 \text{ s}) = 58 \text{ m/s}
\]

b) Average velocity over the first minute after liftoff (\( \Delta t = 60 \) s):

\[
\bar{v} = \frac{\Delta x}{\Delta t} = \frac{at^2}{t} = at
\]

\[
\bar{v} = (29 \text{ m/s}^2)(60 \text{ s}) = 1740 \text{ m/s}
\]
SELF-EXPLANATION PROMPTS

1. Why does $\Delta x$ become $at^2$ and $\Delta t$ become $t$ when calculating average velocity?

2. Describe the motion of the rocket as shown in the position $x$ versus time $t$ graph.

3. How do you expect the instantaneous velocity after one minute to compare to the average velocity calculated in part (b)? Calculate the instantaneous velocity after one minute.
Pre-Class Problem

STATEMENT OF THE PROBLEM

A large meteor is 9700 km away and heading straight towards the Moon. It is travelling at a speed such that it would impact the Moon in 15 minutes, but instead it collides with a smaller meteor, knocking it off its original path at a 26° angle but maintaining its original speed. With this new trajectory, how much longer will it take for the meteor to impact the Moon?

Answer: ~100 seconds
Preflight Questions

1. What topics did you find most challenging from the reading?

2. Solve the following system of equations for \( r \) and \( s \).

\[
\begin{align*}
    r - 2s &= 5 \\
    3r &= -s - 6
\end{align*}
\]

a) \( r = -3.40, \ s = 4.20 \)
b) \( r = -2.43, \ s = 1.29 \)
c) \( r = 3.40, \ s = 4.20 \)
d) \( r = -1.48, \ s = -1.57 \)
e) \( r = -1.00, \ s = -3.00 \)

3. It is possible for an object to have, at the same time...

   a) ... both zero velocity and non-zero acceleration.
   b) ... both non-zero velocity and zero acceleration.
   c) Both (a) and (b) are possible.
   d) Neither (a) nor (b) are possible.

4. CRITICAL THINKING: Explain the difference between average and instantaneous speed/velocity/acceleration. (Hint: You should consider the quantity of time.)
Homework Problems

1.16
Lesson 2

Displacement, Velocity, and Acceleration

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</tr>
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- There is an optional *Equation Dictionary* entry in Appendix D for this lesson (1 PF pt).

Learning Objectives

[Obj 4] Explain the relationship between position, displacement, speed, velocity, and acceleration for an object moving in one and two dimensions.

[Obj 5] Construct and interpret graphs of position, velocity, and acceleration for an object moving in one and two dimensions.

[Obj 6] Explain the difference between instantaneous and average velocity, and between instantaneous and average acceleration.

[Obj 7] Use mathematical and graphical methods to calculate instantaneous and average velocity and instantaneous and average acceleration in one and two dimensions.

[Obj 8] Use equations of motion to solve problems involving motion with constant acceleration.

[Obj 9] Use calculus to solve problems involving motion with non-constant acceleration.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

Drag racing is an acceleration competition that takes place over a level ¼ mile track. A dragster starts from rest and has to complete the ¼ mile (402.3 m) run. The time is very short so the reaction time (the time it takes the driver to start after the green light comes on) is important. The driver with the shortest overall time (run time + reaction time) is the winner.

The national record overall time is 4.42 seconds.

a) Assuming that the acceleration was constant (to get a simple estimate of the acceleration), what was the acceleration in the winning run?

b) What was the average speed of the dragster?

c) Again assuming constant acceleration, what was the final speed as the dragster crossed the finish line?

STRATEGY

This problem assumes constant acceleration and asks us to relate the given time to the speed and acceleration of the dragster. We will use the definition of average speed and equations of motion to solve this problem.

IMPLEMENTATION

For part (a) we apply the relation \( x = x_0 + v_0 t + \frac{1}{2} a t^2 \).

For part (b) we apply the relation for average speed

\[
\bar{v} = \frac{\Delta x}{\Delta t} = \frac{x-x_0}{t}
\]

For part (c) we use the equation for average acceleration

\[
\bar{a} = \frac{\Delta v}{\Delta t} = \frac{v_f-v_0}{t}
\]
CALCULATION

a) Acceleration of the winning run:

The initial velocity $v_0$ is zero, so $x = x_0 + v_0 t + \frac{1}{2} at^2$ simplifies to $x = x_0 + \frac{1}{2} at^2$.

Solving for acceleration gives $a = \frac{2(x-x_0)}{t^2} = \frac{2 \cdot 402.3 \text{ m}}{(4.42 \text{ s})^2} = 41 \text{ m/s}^2$

b) Average speed of the dragster:

$$\bar{v} = \frac{x - x_0}{\Delta t} = \frac{402.3 \text{ m}}{4.42 \text{ s}} = 91 \text{ m/s} = 204 \text{ mph}$$

c) Final speed of the dragster (assuming constant acceleration):

Using the acceleration from part (a), $\ddot{a} = \frac{v_f - v_0}{\Delta t}$ can be written as $v_f - v_0 = a\Delta t$

Since the dragster starts from rest, $v_f = 41 \frac{\text{m}}{\text{s}} \cdot 4.42 \text{ s} = 181 \text{ m/s} = 405 \text{ mph}$

Note: Acceleration and final speed are not measured in drag races; the average speed during the last 20 meters is measured. In the record run, the average speed during the last 20 meters was 336 mph.

SELF-EXPLANATION PROMPTS

1. In your textbook look up the derivations of the equations used in parts (a) and (b) above and summarize in your own words how these relations are obtained.

2. Is it valid to use the relation $x = x_0 + v_0 t + \frac{1}{2} at^2$ if acceleration is not constant? Go to the assigned reading in the textbook and find what assumption was made in the derivation of the equation.

3. What is the relation between initial speed and final speed during a time interval when the acceleration is constant?
Pre-Class Problem

STATEMENT OF THE PROBLEM

On the way to the Moon the first stage engine of the Saturn V moon rocket fired for 156 seconds to lift the craft 38 miles (61,155 meters). What is the average acceleration of Saturn V during this stage?

Answer: $5 \text{ m/s}^2$

Try It! (1pt): What is the speed of the Saturn V at the end of this stage? Answer: $5 \text{ m/s}^2$

Documentation Statement:
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. The following graphs depict the velocities of four objects moving in one dimension. Which object has the greatest displacement during the time interval shown?

   ![Graphs of Velocity vs. Time](image)
   
   a)  
   b)  
   c)  
   d)  

3. Which of the following arrows correspond to a time at which the instantaneous velocity is greater than the average velocity over the time interval shown?

   ![Position vs. Time Graphs](image)
   
   a)  
   b)  
   c)  
   d)  

4. CRITICAL THINKING: Does a car odometer measure displacement or distance? Explain.

   Explain.
Homework Problems

2.20
2.79
Lesson 3

Lab 1 – Acceleration Due to Gravity

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- There is a LAB this lesson.

Learning Objectives

[Obj 10] Solve problems involving free-fall motion with constant gravitational acceleration.

Notes
Pre-Lab Questions

1. Briefly describe the purpose and goals of this lab. (One to two complete sentences)

2. What are the relevant concepts and equations that you will be using in the lab?

3. In the setup of Part 1 of the lab, you are asked to measure the angle of the inclined track. How will you determine the angle of the incline?

4. In Part 1 of the lab, your group will measure the time it takes for an un-weighted air track cart to travel different distances down an incline. In Part 2, your group will measure the time it takes for a weighted air track cart to travel the same distances down an incline. How do you expect the times to compare between the weighted and un-weighted carts? Briefly explain your reasoning.

5. When graphing the data in part I and II, you are asked to plot $\vec{v}^2$ vs. $x$. Explain the reasons behind plotting the data in such a way.
Lab Notes
Homework Problems

2.38
2.42
2.78
Lesson 4

Two-Dimensional & Projectile Motion

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Learning Objectives

[Obj 11] Express vectors both in component form and in magnitude-direction form.

[Obj 12] Use mathematical and graphical methods to perform vector addition, vector subtraction, and scalar multiplication.

[Obj 13] Use vectors to represent position, velocity, and acceleration.

[Obj 14] Describe how the effects of acceleration depend upon the direction of the acceleration vector relative to the velocity vector.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

An aircraft has a velocity of \( \vec{v}_p = 70\hat{i} + 50\hat{j} \text{ m/s}. \) The wind pushes the aircraft with a velocity of \( \vec{v}_w = 45\hat{i} - 40\hat{j} \text{ m/s}. \) What is the resulting final velocity of the plane, \( \vec{v}_{pf}? \)

STRATEGY

Adding vectors is done by adding the \( x \)-components and the \( y \)-components to construct the net velocity vector.

IMPLEMENTATION

Add the components of the two vectors to build the final vector as:

\[
(x\text{-component total})\hat{i} + (y\text{-component total})\hat{j}
\]

CALCULATION

\[
\vec{v}_p + \vec{v}_w = \vec{v}_{pf} = (v_{px} + v_{wx})\hat{i} + (v_{py} + v_{wy})\hat{j}
\]

\[
\vec{v}_{pf} = (70 + 45)\hat{i} \text{ m/s} + (50 - 40)\hat{j} \text{ m/s} = (115\hat{i} + 10\hat{j}) \text{ m/s}
\]
SELF-EXPLANATION PROMPTS

1. Superposition of vectors is the process of adding vectors. Why do you add the $x$- and $y$-components separately?

2. When components are combined, are the absolute values of the components used or do the components retain their negative signs if they have them?

3. Describe a) what additional information you would need to be given to determine the acceleration of the plane in this problem and b) what steps you would use to calculate the acceleration of the plane.
Pre-Class Problem

STATEMENT OF THE PROBLEM

An aircraft has an initial velocity of $\vec{v}_{\text{initial}} = 70\hat{i} + 50\hat{j}$ m/s. It experiences an acceleration of $\vec{a} = 2.5\hat{i} - 2\hat{j}$ m/s$^2$ as the result of a strong wind. After 20 s in this wind, what is the new velocity of the aircraft?

Answer: $\vec{v}_{\text{final}} = 120\hat{i} + 10\hat{j}$ m/s
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. An object is initially moving in the positive x-direction and then experiences acceleration in the positive y-direction. Which of the graphs depicts the x- and y-positions of the object while accelerating?

![Graphs a), b), c), d) are shown here.]

3. The position \( \vec{r} \) of a particle as a function of time \( t \) is \( \vec{r}(t) = \left( \frac{5}{2} t^2 + 5 \right) \hat{i} + (t^2 - 2) \hat{j} \). Which statement is true concerning the particle?

   a) The particle is located at the origin at \( t = 0 \).
   b) \( v(1) = 5 \text{ m/s} \)
   c) \( \vec{v}(t) = \left( \frac{5}{2} t^2 + 5 \right) \hat{i} + (2t - 2) \hat{j} \text{ m/s} \)
   d) \( a(4) = 19/2 \text{ m/s}^2 \)
   e) \( \vec{a}(t) = \left( \frac{15}{4} \sqrt{t} \right) \hat{i} + 2\hat{j} \text{ m/s}^2 \)
   f) Acceleration of the particle is constant.

4. CRITICAL THINKING: Can an object have a northward velocity and southward acceleration? Explain.
Homework Problems

3.34
3.53

Documentation Statement:
3.54
Lesson 5

*Projectile Motion*

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- There is an optional *Equation Dictionary* entry in *Appendix D* for this lesson (1 PF pt).
- *There is an EXAM-PREP QUIZ this lesson.*

**Learning Objectives**

[Obj 14] Describe how the effects of acceleration depend upon the direction of the acceleration vector relative to the velocity vector.

[Obj 15] Solve problems involving projectile motion under constant gravitational acceleration.

**Notes**
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A vintage bomber is participating in an airshow and plans to conduct a bombing run using an “explosive” flour bag. If the aircraft is flying at 75 m/s and releases the flour bomb 1500 meters above the ground, how far back from the target must the pilot release this flour bomb (the release distance x)? How fast is the bomb moving in the horizontal and vertical directions when it hits the ground?

STRATEGY

This is a projectile motion problem where the only acceleration affecting the motion is assumed to be due to gravity, acting vertically downward. We need to apply the basic kinematics equations separately for the motion in the horizontal, x-direction, and the vertical, y-direction. In this problem there is no horizontal acceleration, so the release distance will be the horizontal velocity times the flight time. The flight time will come from analyzing the vertical motion – knowing the total distance and the bomb’s initial vertical velocity. The kinematics equations we will need are \( v = v_0 + at \) and \( x_f = x_0 + v_0t + \frac{1}{2}at^2 \). These equations can be written for both motion in the x- and y-directions with the flight time \( t \) being a common variable.

IMPLEMENTATION

First, we need to establish an origin and coordinate system. Let’s set the origin at the point of release of the bomb with the x-axis pointed to the right and the y-axis pointed up (in a standard configuration). Now, we will determine the flight time (i.e. the time that the flour bomb travels from release to impact). The aircraft is flying in level flight, so the initial velocity in the y-direction \( v_{oy} \) is zero. Also, the only acceleration is due to gravity, acting in a downward direction \( g = -9.8 \text{ m/s}^2 \).

We will manipulate \( y_f = y_0 + v_{oy}t + \frac{1}{2}a_yt^2 \) and solve for flight time. Note that using our origin set at the point of release, the final position \( (y_f) \) will be a negative 1500 m.
Now that we have the flight time, we will use \( x_f = x_0 + v_{ox}t + \frac{1}{2}a_xt^2 \) to solve for the release distance and \( v = v_0 + at \) to determine the vertical speed of the bomb. There is no horizontal acceleration, so the horizontal velocity of the bomb is the same as when it was part of the aircraft.

**CALCULATION**

First, determine the flight time in the vertical direction.

Starting with \( y_f - y_0 = \Delta y = v_{oy}t + \frac{1}{2}a_yt^2 \), we get \((-1500 \text{ m} - 0 \text{ m}) = 0 + \frac{1}{2}(-9.8 \text{ m/s}^2)t^2\)

\[ 2(1500 \text{ m})/(9.8 \text{ m/s}^2) = t^2 \text{ and } t = 17.5 \text{ s}. \]

Next, determine the how far back the bomb is released in the horizontal.

Starting with \( x_f - x_0 = v_{ox}t + \frac{1}{2}a_xt^2 \), we get \( \Delta x = \left(75 \text{ m} \right)(17.5 \text{ s}) + 0 = 1312 \text{ m}. \)

Finally, solve for the final bomb velocity in the vertical:

Starting with \( v_{fy} = v_{oy} + a_yt \) and \( v_{fy} = 0 + (-9.8 \text{ m/s}^2)(12.4 \text{ s}) = -171.5 \text{ m/s} \)

In addition, \( v_{fx} = 75 \text{ m/s} \) since there is no acceleration in the horizontal.

**SELF-EXPLANATION PROMPT**

1. Why is the final position, \( y_f \), a negative quantity?

2. What would be different if we were to designate the origin at the ground level below the release point?

3. What would happen if the initial velocity, \( v_{oy} \), in the vertical was not zero?
**Pre-Class Problem**

**STATEMENT OF THE PROBLEM**

A cannon on a cliff fires at a ship in a pirate movie. The ship is 200 m from the cliff and the initial velocity of the launched cannonball is \( \vec{v}_0 = 60 \hat{i} + 20 \hat{j} \text{ m/s} \). If the cannonball hits the ship, a) how high is the cliff, and b) what is the firing angle?

Answers: 12 m, 18.4°
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. A snowball is thrown vertically upward from a moving sled traveling on a straight, level road at a constant speed. Neglecting air resistance, the snowball will land

   a) in front of the sled.
   b) on the sled.
   c) behind the sled.
   d) The answer depends on the speed of the sled.

3. Two identical masses are shot out of a cannon sitting on a flat surface. The cannon is adjusted such that the horizontal velocity component of the cannonballs are equal. Object 1, a red cannonball, is shot upward at an angle of 30° with respect to the horizontal. Object 2, a blue cannonball, is shot upwards at an angle of 60° with respect to the horizontal. Which ball will hit the ground furthest from the cannon?

   a) The red cannonball.
   b) The blue cannonball.
   c) Both cannonballs will hit at the same spot.
   d) The cannonballs will only go up and down.
   e) The answer cannot be determined from the given data.

4. CRITICAL THINKING: A high jumper and a long jumper are both human projectiles, but with slightly different goals. The high jumper wants to travel over a high bar without touching it, and the long jumper wants to travel as great a distance as possible without touching the ground. Describe how the x- and y-components of the initial velocity vector should differ between the two types of jumpers.
Homework Problems

3.55
Lesson 6

Lab 2 – Projectile Motion

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- There is a LAB this lesson.

Learning Objectives

[Obj 15] Solve problems involving projectile motion under constant gravitational acceleration.

Notes
Pre-Lab Questions

1. Briefly describe the purpose and goals of this lab. (One to two complete sentences)

2. An object is launched horizontally from a height \( h \) with velocity \( v \). How much time \( t \) does it take for the object to reach the level ground below?

   a) \( t = \sqrt{\frac{2h}{g}} \)
   b) \( t = \sqrt{\frac{g}{2h}} \)
   c) \( t = \frac{2h}{g} \)
   d) \( t = \frac{v}{g} \)

3. You will be launching a small air compression rocket for this lab. First, you will launch the rocket vertically and measure the time of flight. Derive an equation that relates time of flight, \( t \), to initial velocity, \( v_0 \), for the rocket.

4. In the second part of the lab, you will launch the rocket at an angle, \( \theta \), and a height, \( h \), above level ground. Using \( \theta \), \( h \), and initial velocity \( v_0 \) as known quantities, derive an expression for the horizontal range, \( \Delta x \), that the rocket will travel.
Homework Problems

MP
Lesson 7

*Acceleration in Circular Motion*

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**Learning Objectives**

[Obj 16] Explain why uniform circular motion involves acceleration.

[Obj 17] Solve problems involving uniform and nonuniform circular motion.

**Notes**
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

An aircraft traveling at a constant 150 m/s makes a 360° turn at a constant altitude (referred to as level flight). If the aircraft’s acceleration toward the center of the turn is 1.5 g, what is the radius of the turn?

STRATEGY

This is a problem involving uniform circular motion (UCM), where several things in the horizontal are uniform: radius (r), tangential speed (v_tan), and the center-directed acceleration (a_centripetal). The aircraft experiences NO acceleration in the vertical direction. The center-directed acceleration (a_centripetal) is related to the tangential velocity by the UCM basic relationship: 

\[ a_{centripetal} = \frac{v_{tan}^2}{r} \]

IMPLEMENTATION

First, we need to determine the magnitude of the center-directed acceleration. We are given that it is 1.5 g. This means 1.5 times the acceleration due to gravity (9.8 m/s²). Next, we will manipulate the UCM basic relationship so that \( r \) is alone on the left side of the equation. We then solve for the radius.

CALCULATION

First, manipulate the UCM basic relationship to solve for \( r \):

\[ a_{centripetal} = \frac{v_{tan}^2}{r} \text{ becomes } r = \frac{v_{tan}^2}{a_{centripetal}} \]

Now, substitute and solve:

\[ r = \frac{(150 \text{ m/s})^2}{(1.5)(9.8 \text{ m/s}^2)} = 1530 \text{ m} \]

Notice that the units resolve as: \( \frac{(\text{m}^2/\text{s}^2)}{(\text{m}/\text{s}^2)} = \text{m} \)
SELF-EXPLANATION PROMPTS

1. In this problem, the aircraft is traveling at a constant speed of 150 m/s. Is this aircraft (or any object executing uniform circular motion) undergoing acceleration? Explain.

2. How do you know that the acceleration in the vertical is zero?

3. What causes the center-directed acceleration?
Pre-Class Problem

STATEMENT OF THE PROBLEM

A 650-kg Formula One race car executes a portion of a circular turn at 20 m/s. The radius of the turn is 50 meters. What acceleration must the friction of the tires generate in order to accomplish this turn? What is the direction of that acceleration?

Try It! (1pt): Describe and draw the acceleration vector if the car’s speed was increasing as it executed the turn.

Answer: 8 m/s², towards the center of the turn.

Documentation Statement:
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. When a car traveling at a constant speed goes around a curve on a level road, what is the direction of acceleration?

   a) There is no acceleration.
   b) The car is accelerating toward the center of the curve.
   c) The car is accelerating away from the center of the curve.
   d) The acceleration is in the same direction the car is traveling.

3. Rank in order the radial accelerations of the following objects from largest to smallest.

   ![Diagrams showing radial accelerations](diagrams)

   a) $B = E > A = C = D$
   b) $B > A = C = E > D$
   c) $B > E > A = C > D$
   d) $D = E > A = B = D$

4. CRITICAL THINKING: When you ride in a vehicle that is making a turn your body feels pushed outward. Reconcile this fact with the physics statement that the real acceleration of your body is inward towards the center of the turn.
Homework Problems

MP
Lesson 8

GRADED REVIEW 1

Learning Objectives

[Obj 1] Convert physical measurements from various units to the standard SI units of meters, kilograms, and seconds.

[Obj 2] Express quantities using scientific notation and perform addition, subtraction, multiplication, division, and exponentiation on them.

[Obj 3] Identify the number of significant figures given in a problem statement, and express the answer using the correct number of significant figures.

[Obj 4] Explain the relationship between position, displacement, speed, velocity, and acceleration for an object moving in one and two dimensions.

[Obj 5] Construct and interpret graphs of position, velocity, and acceleration for an object moving in one and two dimensions.

[Obj 6] Explain the difference between instantaneous and average velocity, and between instantaneous and average acceleration.

[Obj 7] Use mathematical and graphical methods to calculate instantaneous and average velocity and instantaneous and average acceleration in one and two dimensions.

[Obj 8] Use equations of motion to solve problems involving motion with constant acceleration.

[Obj 9] Use calculus to solve problems involving motion with non-constant acceleration.

[Obj 10] Solve problems involving free-fall motion with constant gravitational acceleration.

[Obj 11] Express vectors both in component form and in magnitude-direction form.

[Obj 12] Use mathematical and graphical methods to perform vector addition, vector subtraction, and scalar multiplication.

[Obj 13] Use vectors to represent position, velocity, and acceleration.

[Obj 14] Describe how the effects of acceleration depend upon the direction of the acceleration vector relative to the velocity vector.

[Obj 15] Solve problems involving projectile motion under constant gravitational acceleration.

[Obj 16] Explain why uniform circular motion involves acceleration.

[Obj 17] Solve problems involving uniform and nonuniform circular motion.

Notes

Documentation Statement:
Lesson 1: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

Susan is driving at 50 mph to pick up her friend at the airport. Her friend’s flight lands in 30 minutes, and she is 40 mi away from the airport. Will Susan be able to pick up her friend on time? If so, how long will it take for her to arrive at her current speed? If not, what will she have to change her speed to in order to arrive at the airport on time?

STRATEGY (Fill in the blanks.)

We will need to first determine if Susan’s current speed is sufficient to allow her to arrive within 30 minutes. We can calculate the speed necessary to cover the given remaining distance and compare it to her current speed. If her current speed is greater than the needed speed, then she will be able to arrive on time. If her current speed is less than the needed speed, then she will need to modify her current speed.

CALCULATION (Fill in the blanks.)

Needed speed based on remaining distance:

\[ \bar{v}_{\text{needed}} = \frac{\Delta x}{\Delta t} = \frac{40 \text{ mi}}{0.5 \text{ hr}} = \underline{____} \text{ mi/hr} \]

\[ \bar{v}_{\text{needed}} > \bar{v}_{\text{current}} \quad \text{or} \quad \bar{v}_{\text{needed}} < \bar{v}_{\text{current}} \quad \text{(circle one)} \]

If \( \bar{v}_{\text{needed}} < \bar{v}_{\text{current}} \), how long will it take to arrive?

\[ \Delta t = \frac{\Delta x}{\bar{v}_{\text{current}}} = \underline{____} \text{ hr} \]

If \( \bar{v}_{\text{needed}} > \bar{v}_{\text{current}} \), what will Susan have to change her speed to?

SELF-EXPLANATION PROMPTS

1. What speed would Susan need to arrive exactly on time?

Optional Practice Problems: 2.21, 2.43, 2.47

Documentation Statement:
Lesson 2: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

The acceleration due to gravity in free fall is about 9.8 m/s². A typical speed for an arrow shot from a bow is 76.2 m/s. If such an arrow is shot straight up, and air resistance is neglected, how high would it go?

STRATEGY (Fill in the blanks.)

In our case \( v = \) _______________, \( v_0 = \) _______________,
\[ a = \] ______ (watch the sign!), \( x - x_0 \) is the height.

Now, if we eliminate the variable \( t \) between
\[ x = x_0 + v_0 t + \frac{1}{2} a t^2 \] and \( v = v_0 + at \)
we get
\[ v^2 = v_0^2 + 2a(x - x_0) \]

CALCULATION (Fill in the blanks.)

height = ________________ = 296 m

That is almost 0.2 mile and probably unrealistic.

SELF-EXPLANATION PROMPTS

1. Perform the derivation in the STRATEGY section.

2. Which quantities in \( v^2 - v_0^2 = 2a(x - x_0) \) are positive, which are negative?

Optional Practice Problems: 2.37, 2.51, 2.61, 2.69
Lesson 4: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

Two vectors are \( \vec{A} = 7\hat{i} - 4\hat{j} \) and \( \vec{B} = -3\hat{i} - 2\hat{j} \). What is the vector \( \vec{C} = \vec{B} - \vec{A} \) ?

STRATEGY (Fill in the blanks.)

Perform this subtraction by dealing with the \( x \)-components and the \( y \)-components separately.

IMPLEMENTATION (Fill in the blanks.)

The \( A_x \) and \( B_x \) components are:

\[
A_x = \underline{\phantom{-}7}, \quad B_x = \underline{\phantom{-}3}
\]

The \( A_y \) and \( B_y \) components:

\[
A_y = \underline{\phantom{-}4}, \quad B_y = \underline{\phantom{-}2}
\]

CALCULATION (Supply the needed signs, or numbers)

\[
\vec{C}_x = 3 - 7 \quad \text{and} \quad \vec{C}_y = -2\quad 4
\]

\[
\vec{C} = \underline{\phantom{-}4}\hat{i} + \underline{\phantom{-}1}\hat{j}
\]

SELF-EXPLANATION PROMPTS

1. What is the magnitude of the vector \( \vec{C} \) ?

2. How do we handle the subtraction of a “negative” component, like the “\((-4/3)\hat{j}\)”?

Optional Practice Problems: 3.11, 3.14, 3.31
Lesson 5: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A vintage bomber participating in an air show wants to drop a bomb that stays in the air for 15 seconds before impact. If the horizontal velocity of the plane is 75 m/s, determine the required launch altitude.

STRATEGY (Fill in the blanks.)

Let’s set the ______ at the vertical point where the bomb is ______

We will use $v = v_0 + at$ written in the _____ dimension, using _____ for the time of flight.

The $v_0$ will still be _____ in the vertical, and the _____ will still be ____ $9.8 \text{ m/s}^2$.

CALCULATION (Fill in the blanks)

$y_f - y_0 = v_{0y}t + \frac{1}{2}gt^2$

$y_f - ____ \text{ m} = (0)(____ \text{ s}) + \frac{1}{2}(-9.8 \text{ m/s}^2)(15 \text{ s})^2 = 1103 \text{ m}$

SELF-EXPLANATION PROMPTS

1. How are the flight times in the horizontal and the vertical directions connected?

2. How would an initial velocity in the vertical affect the answer in this problem?

3. How is the negative direction of gravity’s effect accounted for in order to result in a positive value for $y_0$?

Optional Practice Problems: 3.33, 3.62
Lesson 7: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

This hammer thrower releases the hammer ball with a tangential speed of 21 m/s when the ball is 1.8 m from the center of the athlete’s rotation. a) What is the centripetal acceleration of the ball at the instant it is released? b) How does this acceleration compare to the acceleration due to gravity?

STRATEGY (Fill in the blanks.)

To solve this problem we use the UCM basic relationship

\[ a_{\text{centripetal}} = \text{______________} \]

CALCULATION (Fill in the blanks.)

\[ a_{\text{centripetal}} = \text{____________________} = 245 \, \text{m/s}^2 \]

\[ a_{\text{centripetal}} \text{ is directed __________ and is _______ times larger than the acceleration due to gravity, which is directed ______________.} \]

SELF-EXPLANATION PROMPTS

1. What object provides the acceleration of the hammer ball?

2. What is the direction of the net acceleration of the hammer ball just before it is released?

Optional Practice Problems: 3.38, 3.39, 3.40
Lesson 9

Forces and Newton's Laws of Motion

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Learning Objectives

[Obj 18] Explain the concept of force and how forces cause change in motion.
[Obj 19] State Newton’s three laws of motion and give examples illustrating each law.
[Obj 20] Explain the difference between mass and weight.

Notes
Worked Examples

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A tow truck is pulling a disabled 1200-kg car along a level road. The tow-rope is parallel to the road. Starting from rest, the speed increases to 2 m/s over a 20 meters distance. What is the tension in the rope? Assume friction is negligible.

STRATEGY

Newton’s Second Law as applied to the car states that the acceleration of the car \( \ddot{a} \) is given by \( \ddot{a} = \frac{F_{\text{net}}}{M} \). We know the mass of the car, and we can use kinematics to find the acceleration of the car. Newton’s Second Law can then be used to obtain the net force.

IMPLEMENTATION

To get the net force, we multiply the acceleration of the car, obtained from the kinematics equation \( v_f^2 - v_i^2 = 2a(x_f - x_i) \), by the mass of the car.

CALCULATION

\[
\sum \vec{F} = m\ddot{a}
\]

\[
F = M \frac{v_f^2 - v_i^2}{2(x_f - x_i)} = 1200 \text{ kg} \left( \frac{(4 - 0) \text{ m}^2/\text{s}^2}{2(20 \text{ m})} \right) = 120 \text{ N}
\]

The force unit \( \text{kg m/s}^2 \) is called a **newton**, \( \text{N} \), in honor of Isaac Newton.
SELF-EXPLANATION PROMPTS

1. The unit of force is a newton which is given the symbol N. Express the newton in terms of the fundamental SI units.

2. Find the definition of “tension in a rope” in your textbook and rephrase it in your own words.

3. What change would you make in the calculation if the tow-rope was directed at an angle?
Pre-Class Problem

A 45-g golf ball at rest is hit by a club with a force of 5.0 N. a) What is the ball's acceleration immediately after it is hit? b) How far does the ball travel in the first tenth of a second?

Answer: 110 m/s², 0.56 m
Preflight Questions

1. What topics did you find most challenging from the reading?

2. A 200-kg rock is being pulled upward with an acceleration of 3 m/s². The net force on the rock is
   a) 200 N up
   b) 200 N down
   c) Zero
   d) None of the above.

3. The net force vector for an object in motion is
   a) always in the same direction as the object’s acceleration vector.
   b) sometimes in the same direction as the object’s acceleration vector.
   c) always in the same direction as the object’s velocity vector.
   d) always in the same direction as the object’s displacement vector.

4. CRITICAL THINKING: The take-off mass of an F-16 is 16,875 kg. Its engine can exert a force of 105,840 N. If you mounted the F-16 engine on a car, what acceleration would you get? Use a reasonable estimate for the mass of a car and explain how you obtained your answer.
Homework Problems

4.15
Lesson 10

Using Newton's Laws

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- There is an optional Equation Dictionary entry in Appendix D for this lesson (1 PF pt).

Learning Objectives

[Obj 19] State Newton’s three laws of motion and give examples illustrating each law.

[Obj 20] Explain the difference between mass and weight.

[Obj 21] Construct free-body diagrams using vectors to represent individual forces acting on an object, and evaluate the net force using vector addition.

[Obj 22] Use Newton’s laws of motion to solve problems involving multiple forces acting on a single object.

[Obj 23] Use Newton’s laws of motion to solve problems involving multiple objects.

Notes
Worked Examples

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A team of dogs is pulling two connected sleds with a constant acceleration of 2.3 m/s². The passenger sled, connected to the dogs in front, has a mass of 96 kg. The cargo sled, tied to the front sled, has a mass of 42 kg. For now, we assume that the retarding friction is much smaller than the force exerted by the dogs.

a) How much is the force that the dogs exert on the sled train?

b) With what force is the cargo sled pulling back on the passenger sled?

STRATEGY

The accelerating sleds are subject to Newton’s Second Law, which states that the acceleration of an object is proportional to the applied force and inversely proportional to the mass of the accelerating object. To answer part (a), we apply the law to the sled train with the combined mass of 138 kg and solve the resulting equation for the unknown applied force.

Newton’s Third Law states that when two objects are connected and the first one exerts a force on the second one, the second one responds with a reaction force of the same magnitude, acting back on the first one. Since we know the mass and the acceleration of the cargo sled, we can determine the applied force exerted on the cargo sled by the passenger sled. It is the passenger sled that pulls the cargo sled, not the dogs directly. The reaction force exerted by the cargo sled on the passenger sled has the same magnitude as the force exerted by the passenger sled on the cargo sled and is pulling back on it.

Score (3)
IMPLEMENTATION

Let's label the force exerted by the dog team \( \vec{F}_d \) on the sled team.
Let's label the force exerted by the passenger sled on the cargo sled \( \vec{F}_{pc} \).
Let's label the force exerted by the cargo sled on the passenger sled \( \vec{F}_{cp} \).

CALCULATION

For each part we apply Newton's Second Law \( \vec{F} = m\vec{a} \).

a) \[ 2.3 \text{ m/s}^2 = \frac{\vec{F}_d}{138 \text{ kg}} \quad \vec{F}_d = 320 \text{ N in the forward direction} \]

b) \[ 2.3 \text{ m/s}^2 = \frac{\vec{F}_{pc}}{42 \text{ kg}} \quad \vec{F}_{pc} = 97 \text{ N in the forward direction} \]

The dogs pull the sled train forward with a force of 320 N.
The cargo sled pulls back on the passenger sled with a force of 97 N.

SELF-EXPLANATION PROMPTS

1. Rephrase Newton's Second Law in your own words.

2. What is the net force on the passenger sled?

3. If the cargo sled was removed, how do you expect the force applied by the dog team to change in order to obtain the same acceleration of 2.3 m/s\(^2\) for just the passenger sled? Calculate the force exerted by the dog team \( \vec{F}_d \) for this scenario.
Pre-Class Problem

STATEMENT OF THE PROBLEM

A 12-kg child is riding in a 4100-kg elevator which is accelerating upward at a constant 1.3 m/s². What is the force that the elevator exerts on the child? What is the force the child exerts on the elevator?

Answer: 133 N, -133 N

Try it! (1PF pt): If the child was standing on a scale in the elevator, what would the scale read when the elevator was (a) stationary and (b) accelerating upward at 1.3 m/s²? Show all your work.

Answer: 133 N, -133 N
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. Two forces of equal magnitude act on the same object. Which of the following must be true?
   
   a) The object is moving.
   b) The object is accelerating.
   c) If the object is initially at rest, it cannot remain at rest.
   d) The two forces form a third-law pair.
   e) None of the above.

3. Two blocks are hanging motionless from the ceiling as shown in the diagram. Which of the following is true?

   a) $\vec{T}_1 < \vec{T}_2$
   b) $\vec{T}_1 = \vec{T}_2$
   c) $\vec{T}_1 > \vec{T}_2$
   d) $\vec{T}_1 < \vec{T}_2$ only if $m_1 < m_2$

4. CRITICAL THINKING: The term "weight" in physics has the following very specific meaning: "The weight of an object is the name given to a particular force: the gravitational force exerted by the earth on the object, giving it an acceleration of 9.8 m/s$^2$ near the surface of Earth."

   In ordinary speech the use of "weight" is nowhere nearly so precise. Explain whether the following usages are scientifically correct.
   
   a) A 3-kg object has a weight of about 30 N at the surface of Earth.
   b) A 120-lb person weighs about 55 kg.
   c) An astronaut orbiting Earth experiences weightlessness.
   d) If you eat too much you may gain weight.
Homework Problems

4.34
4.47
Lesson 11

Newton's Laws in Two Dimensions

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Learning Objectives

[Obj 22] Use Newton's laws of motion to solve problems involving multiple forces acting on a single object.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 50-kg block is on a frictionless 30° ramp. Determine the block’s acceleration down the ramp.

STRATEGY

**Newton’s Second Law** as applied to the block states that the acceleration of the block \( \ddot{a} \) is given by \( \ddot{a} = \frac{F_{\text{net}}}{M} \). In this problem, we have two forces acting on the block: weight \( \vec{w} \) and the normal force \( \vec{n} \). These forces act in the \( x \)- and \( y \)-directions, so we need to separate each force into its components. Once in component form, we can sum the forces in each direction and apply Newton’s Second Law to find acceleration. Because the motion of the block is along the incline, we “tilt” the coordinate system of our free-body diagram to align with the incline of the ramp and the normal force that is acting on the block.

IMPLEMENTATION

Let’s draw a free-body diagram for our object of interest: the block. There are two forces acting on the block, weight and normal force, that are included in the diagram. Since the block is moving down the ramp, we use a tilted coordinate system. The net force on the block in the \( x \)-direction is:

\[
\sum F_x = ma_x
\]

\[\text{mg} \sin \theta = ma_x\]

The net force on the block in the \( y \)-direction is:

\[
\sum F_y = ma_y
\]

\[n - \text{mg} \cos \theta = ma_y\]
CALCULATION

The acceleration in the y-direction (perpendicular to the incline as defined by our coordinate system) is zero. To find the acceleration of the block, we need to solve for the acceleration in the x-direction $a_x$. Cancelling mass in the net force equation above gives:

$$a_x = g \sin \theta = 9.8 \text{ m/s}^2 \sin 30^\circ = 4.9 \text{ m/s}^2$$

SELF-EXPLANATION PROMPTS

1. Explain why tilting the coordinate system simplified the problem. Think about how the procedure would have changed had traditional $x$-$y$ coordinates been used.

2. Would the answer have changed had the coordinate system been switched, so the positive x-axis was defined as being up the ramp?

3. What would happen to the magnitude of the block's acceleration if the angle of the ramp was increased? What is the maximum acceleration the block can experience? What is the minimum acceleration the block can experience?
**Pre-Class Problem**

**STATEMENT OF THE PROBLEM**

A 3.0-kg box is suspended from a ceiling as shown. What are the magnitudes of the tensions exerted by the ropes attached to the box? Assume the ropes have negligible mass compared to the box. (Hint: Look at Example 5.2 in the textbook. Why is it easier to use a traditional x—y coordinate system rather than tilted for this problem?)

\[ T_1 = 25 \text{ N} \]
\[ T_2 = 11 \text{ N} \]
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. A 5-kg block is pushed across a horizontal floor with a 20-N force directed 20° below the horizontal. What is the magnitude of the normal force on the block?

   a) 49 N  
   b) 6.8 N  
   c) 42 N  
   d) 56 N  
   e) 68 N

3. If Rope 1 remains horizontal and the point at which Rope 2 is tied is moved from A to B, what is true about the tension in the ropes?

   a) $T_1$ remains the same and $T_2$ increases.  
   b) $T_1$ decreases and $T_2$ increases.  
   c) Both $T_1$ and $T_2$ remain the same.  
   d) Both $T_1$ and $T_2$ increase.

4. CRITICAL THINKING: Refer to preflight question 3: Is it possible to attach Rope 2 at point C and have both ropes parallel to the ground? Explain.
Homework Problems

5.16
Lesson 12

*Newton's Laws with Multiple Objects*

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**Learning Objectives**

[Obj 23] Use Newton’s laws of motion to solve problems involving multiple objects.

**Notes**
Worked Examples

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 2,500-kg tractor is pulling a 750-kg cow out of a ravine, as shown. If the tractor applies a force of 20 kN, determine the acceleration of the cow out of the ravine. Assume the rope and pulley are massless and the rope does not stretch.

STRATEGY

There are multiple components in this problem (tractor, rope, pulley, and cow), so we need first to determine which objects are of interest. Once we have identified the objects of interest, we will draw free-body diagrams for each and apply Newton's Second Law (N2L).

IMPLEMENTATION

For this problem, we are only interested in the tractor and the cow since the rope and pulley are massless. Let's draw free-body diagrams for each object and apply Newton's Second Law, summing the forces acting on each object. This operation will give us separate equations that include forces and accelerations. Since the objects are connected by a massless rope that does not stretch, the magnitudes of the tensions and accelerations are the same. We can then solve for the unknown acceleration.

CALCULATION

The net force on the tractor in the \( x \)-direction is:

\[
\sum F_x = m_x
\]

\( F_{\text{applied}} - T = m_{\text{tractor}}a \)
The net force on the cow in the $y$-direction is:

$$\sum F_y = ma_y$$

$$T - w_{cow} = m_{cow}a$$

Combining these two equations gives:

$$F_{applied} - (w_{cow} + m_{cow}a) = m_{tractor}a$$

Solving for acceleration:

$$a = \frac{F_{applied} - w_{cow}}{m_{cow} + m_{tractor}}$$

Substituting in values gives an acceleration of:

$$a = \frac{20000 \text{ N} - (750 \text{ kg} \cdot 9.8 \frac{m}{s^2})}{750 \text{ kg} + 2500 \text{ kg}} = 3.9 \text{ m/s}^2$$

**SELF-EXPLANATION PROMPTS**

1. Explain why the acceleration of the tractor in the $x$-direction is the same as the acceleration of the cow in the $y$-direction.

2. Explain why the weight of the cow is a negative quantity.

3. If the tractor could only apply a 2 kN force, calculate the acceleration of the cow. Describe the motion of the cow+tractor system for this scenario.
Pre-Class Problem

STATEMENT OF THE PROBLEM

A 10-kg cart is connected by a string to a 10-kg weight over a pulley. Assuming that the masses of the string and the pulley can be neglected, find the acceleration of the cart and the tension in the string.

Free-Body Diagram of the Cart (required)

Free-body Diagram of the Weight (required)

Answers: 4.9 m/s², 49 N
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. A bucket attached to a rope is raised out of a well at a constant speed. What can be said about the tension in the rope compared to the weight of the bucket?
   a) Tension is less than the weight of the bucket.
   b) Tension is equal to the weight of the bucket.
   c) Tension is greater than the weight of the bucket.
   d) Cannot be determined from the given information.

3. In Case 1, Block B accelerates Block A across a frictionless table. In Case 2, a force of 98 N accelerates Block A across the same table. The acceleration of Block A is
   a) zero.
   b) greater in Case 1.
   c) greater in Case 2.
   d) the same in both cases.

4. CRITICAL THINKING: When you are in an elevator you often feel a little lighter as the elevator starts to move downward. Explain this feeling based on Newton’s Laws.
Homework Problems

5.19
Lesson 13

Lab 3 – Newton’s Laws

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- There is a LAB this lesson.

Learning Objectives

[Obj 23] Use Newton’s laws of motion to solve problems involving multiple objects.

Notes
Pre-Lab Questions

1. Briefly describe with one or two complete sentences the purpose and goals of this lab.

2. Construct free-body diagrams for $m_1$ and $m_2$ for the following scenario.

Free-Body Diagram: Mass 1

Free-Body Diagram: Mass 2

3. Use Newton’s second law to derive an expression for the acceleration of the masses in terms of $m_1$, $m_2$, $\theta$, and $g$. 

Documentation Statement:
Lesson 14

Newton's Laws in Circular Motion

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- There is an EXAM-PREP QUIZ this lesson.

Learning Objectives

[Obj 16] Explain why uniform circular motion involves acceleration.
[Obj 17] Solve problems involving uniform and nonuniform circular motion.
[Obj 22] Use Newton’s laws of motion to solve problems involving multiple forces acting on a single object.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

An amusement park ride consists of a vertical loop whose diameter is 15 m and a small 150-kg cart that runs on the inside track in the loop. The ride is designed to carry a maximum load of 320 kg.

The cart is given an initial speed at the bottom of the track and is not propelled further. When the cart climbs vertically to the 90° point, its speed is 12.4 m/s. What is the magnitude and direction of the net force on the cart at this point?

STRATEGY

The cart is subject to the force of gravity, which is equal to its mass times the acceleration due to gravity, 9.8 m/s² vertically down.

The cart also is subject to a normal force from the track that is directed towards the center of the loop and acts like a centripetal force. We add the two force vectors to obtain the net force.

IMPLEMENTATION

Normal force: \( n = ma_c = \frac{v^2}{r} \) directed horizontally to the left.

Force due to gravity (weight) \( W_{cart} = mg \) directed vertically downward.

1. The magnitude of the net force is
   \[ F_{net} = \sqrt{W_{cart}^2 + F_c^2} \]

2. The direction of the net force is at an angle
   \[ \theta = \tan^{-1} \frac{g}{a_c} = \tan^{-1} \frac{gr}{v^2} \]

below the horizontal. The net force is causing the cart to slow down as it climbs to track.
CALCULATION

1. $F_{\text{net}} = 3410 \, N$

2. $\theta = 25.4 \, \text{degrees below horizontal, to the left towards the center of the loop.}$

SELF-EXPLANATION PROMPTS

1. Draw free-body diagrams of the cart when it is at the bottom and top of the track.

2. Does the cart travel around the loop at a constant speed? Explain.

3. Describe how the weight, normal force and net force change as the cart moves around the track.
Pre-Class Problem

STATEMENT OF THE PROBLEM

A 50-kg wrecker’s ball is hanging on an 8-m rope that can support a maximum force of 1000 N. If the ball is swung in a vertical circle, what is fastest speed it can have at the lowest point such that the rope won’t break?

Answer: 9.0 m/s
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. An object moves at a constant speed in a circular path. The instantaneous velocity and the instantaneous acceleration vectors are
   a) both tangent to the circular path.
   b) both perpendicular to the circular path.
   c) perpendicular to each other.
   d) opposite to each other.
   e) none of the above.

3. A ball on a string moves around a vertical circle. At the bottom of the circle, the tension in the string
   a) is greater than the weight of the ball.
   b) is less than the weight of the ball.
   c) is equal to the weight of the ball.
   d) may be greater or less than the weight of the ball.

4. CRITICAL THINKING: The figure shown is a view looking down on a horizontal table top. A ball rolls along the gray barrier which exerts a force on the ball, guiding its motion in a circular path. After the ball ceases contact with the barrier, describe the motion of the ball and your reasoning.
## Homework Problems

5.65
5.73
Lesson 15

Newton's Laws with Friction

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Learning Objectives

[Obj 24] Differentiate between the forces of static and kinetic friction and solve problems involving both types of friction.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A team of dogs is pulling two connected sleds with an acceleration of 2.3 m/s². The passenger sled, connected to the dogs in front, has a mass of 96 kg; the cargo sled, tied behind the passenger sled, has a mass of 42 kg. The coefficient of kinetic friction between the steel runs on the sleds and the ice is \( \mu = 0.007 \). How much force does the dog team exert on the sled train?

STRATEGY

The accelerating sleds are subject to Newton’s Second Law (N2L), which states that the acceleration of an object is proportional to the applied force and inversely proportional to the mass of the accelerating object. We apply N2L to the sled train with the combined mass of 138 kg and solve the resulting equation for the unknown applied force, including the frictional force which acts opposite the direction of motion.

IMPLEMENTATION

Let’s label the force exerted by the dog team \( \vec{F}_d \).
Let’s label the force exerted on the cargo sled by passenger sled \( \vec{F}_{cp} \).
Let’s label the force exerted on the passenger sled by cargo sled \( \vec{F}_{pc} \).
Let’s label the force exerted by the kinetic friction \( \vec{f}_k \) on both sleds.

CALCULATION

The net force on the sled team in the x-direction is:

\[
\sum F_x = ma_x
\]

\[
F_d - f_k = ma_x
\]

The net force on the sled team in the y-direction is:

\[
\sum F_y = ma_y
\]

\[
n - w_{sled team} = ma_y
\]
The acceleration in the y-direction is zero, so the normal force is: \( n = w_{sled\ team} \)

The kinetic force is given by: \( f_k = \mu n \)

Substituting into the equation of the net force in the x-directions gives:

\[
F_d - \mu w_{sled\ team} = m_{sled\ team} a_x
\]

**CALCULATION**

\[
F_d - (0.007)(96 + 42) \text{kg} = (96 + 42) \text{kg} (2.3 \text{ m/s}^2)
\]

\[ F_d = 320 \text{ N in the forward direction.} \]

**SELF-EXPLANATION PROMPTS**

1. In Lesson 10 we solved the same problem, but without friction. Explain how the method changes when friction is included.

2. Explain why kinetic friction was used in the problem rather than static friction.

3. Describe the steps used to determine the kinetic friction.
**Pre-Class Problem**

**STATEMENT OF THE PROBLEM**

A 60-kg block is released from rest on a 45° ramp where the coefficient of friction between the block and ramp is 0.4. What is the acceleration of the block?

**Answer:** 4.2 m/s²

Try it! (1pt): Determine the speed of the block at the bottom of the ramp if it starts from rest at the top of the 3-m long ramp. Show your work.

**Answer:** 4.2 m/s²
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. Which statement concerning friction is true?
   a) Static friction is always opposite the direction of motion.
   b) Kinetic friction is always opposite the direction of motion.
   c) Both static and kinetic friction are always opposite the direction of motion.
   d) Neither is always opposite the direction of motion.

3. A box is at rest on the flat bed of a moving truck. Dawn applies the brakes abruptly and the box begins to slide. Which free-body diagram correctly depicts the forces acting on the box and its resulting motion?

4. CRITICAL THINKING: Describe, in your own words, the difference between static friction forces and kinetic friction forces.
Homework Problems

5.43
5.57
Lesson 16

Critical Thinking: Newton’s Laws with Non-constant Mass

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Learning Objectives

[Obj 18] Explain the concept of force and how forces cause change in motion.

Notes
Preflight Questions

1. What topics did you find most challenging from the reading?

2. A rocket lifts off from the launch pad and rises majestically on its flight. The thrust of the rocket results from

   a) the exhaust gases pushing against the ground.
   b) the exhaust gases pushing against the air.
   c) the combustion gases pushing against the rocket.
   d) the equal and opposite reaction to gravity pulling down.
   e) the gravitational energy released by burning fuel.

3. At some point beyond atmospheric space shuttle flight, the 3-main engines stop providing thrust and then the booster tank SEPARATES from the craft. When the connection between the two objects is severed, the velocity of the shuttle

   a) increases.
   b) decreases.
   c) remains unchanged.
   d) The answer depends on the mass of the booster.

4. CRITICAL THINKING: The space shuttle assembly on the launch pad has a mass of about 2 million kg. The exhaust velocity of the propellant gases is about 4000 m/s. The gases are streaming out of the nozzles at the rate of about 18,000 kg/s. Given this information, estimate the acceleration of the space shuttle assembly.
Homework Problems

5.30
5.62
Lesson 17

**GRADED REVIEW 2**

Learning Objectives

[Obj 18] Explain the concept of force and how forces cause change in motion.
[Obj 19] State Newton’s three laws of motion and give examples illustrating each law.
[Obj 20] Explain the difference between mass and weight.
[Obj 21] Construct free-body diagrams using vectors to represent individual forces acting on an object, and evaluate the net force using vector addition.
[Obj 22] Use Newton’s laws of motion to solve problems involving multiple forces acting on a single object.
[Obj 23] Use Newton’s laws of motion to solve problems involving multiple objects.
[Obj 24] Differentiate between the forces of static and kinetic friction and solve problems involving both types of friction.

Notes
Lesson 9: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 1000-kg car is traveling at 10 m/s when a braking force of 500 N is applied. How much time does elapse before the car comes to a complete stop?

STRATEGY (Fill in the blanks.)

Newton’s Second Law as applied to the car states that the acceleration of the car $a$ is given by $a = \frac{F_{\text{net}}}{M}$. We know the mass of the car and the net force, so we can get the deceleration of the car applying Newton’s Second Law. We can then use kinematics to find the stopping time.

CALCULATION (Fill in the blanks.)

\[
a = \ldots = -0.5 \text{ m/s}^2.
\]

\[
 v_f - v_i = \ldots t
\]

\[
t = \ldots = 20 \text{ s}
\]

SELF-EXPLANATION PROMPTS

1. Compare this example to the tow-truck example, step by step.

2. We calculated the acceleration to be $-0.5 \text{ m/s}^2$. What does the minus sign indicate about the car’s acceleration?

Optional Practice Problems: 4.13, 4.15, 4.23
Lesson 10: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

On July 16, 1969, a Saturn V rocket lifted off the pad in Florida on mankind's first trip to the surface of the Moon. The fully-loaded rocket had a mass of $2.8 \times 10^6$ kg. To propel itself upward it generated $34.5 \times 10^6$ N of thrust. What was the initial acceleration of the rocket?

STRATEGY (Fill in the blanks.)

We calculate the acceleration by dividing the net force on the rocket by its mass, $\ddot{a} = \frac{\vec{F}}{m}$.

There is an upward force on the rocket from the thrust of its engines, and a downward force, the weight of the rocket, from gravity acting on the rocket. The net upward force is therefore thrust minus weight.

CALCULATION (Fill in the blanks.)

The weight of the rocket is

$$W = m(______) = 27,440,000 \text{ N}$$

The net upward force on the rocket is

$$F = _______ - _______ = 7,060,000 \text{ N}$$

The initial acceleration of the rocket is

$$a = \frac{\vec{F}}{m} = 2.52 \text{ m/s}^2.$$  

SELF-EXPLANATION PROMPTS

1. What would be the acceleration of a rocket of the same mass if it started from rest in empty space, away from objects that exert gravitational forces like Earth?

2. Further into the lift-off, would you expect the Saturn's acceleration to increase, decrease, or remain the same?

3. What magnitude of thrust would make the Saturn just hover, with no acceleration?

Optional Practice Problems: 4.27, 4.37, 4.45
Lesson 11: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 5-kg ball is suspended from three ropes as shown in the picture. What is the force exerted on the wall by the horizontal rope?

STRATEGY (Fill in the blanks.)

Apply Newton’s Second Law to the junction of the three ropes. The system is not accelerating, so the vector sum of the forces is zero. Decompose the forces into components and solve for the unknown force.

IMPLEMENTATION (Fill in the blanks.)

The forces acting on the vertical rope are: _______, _______, and _______.

The net force in the x-direction is:

\[
\sum F_x = ma_x
\]

_____________________ = ma_x

The net force in the y-direction is:

\[
\sum F_y = ma_y
\]

_____________________ = ma_y

Since _______ = 0, the equation relating the forces \( T_1, T_2 \), and the weight of the ball is:

\( T_1 \quad T_2 \quad m \ddot{g} = 0 \)

CALCULATION

Solving the two equations gives us \( T_2 = 8.00 \text{ N} \)

SELF-EXPLANATION PROMPTS

1. Is it possible to suspend the ball in this example in such a way that both forces \( T_1 \) and \( T_2 \) have horizontal components only? Explain.
2. Are the magnitudes of any of the tensions in the three ropes larger than the weight of the ball?

Optional Practice Problems: 5.15, 5.33, 5.36

Documentation Statement:
Lesson 12: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

Two balls with masses, \( M_1 \) and \( M_2 \), are connected by a rope which passes over a pulley as shown. Find the accelerations of the balls as they are released from rest. Assume that the rope does not stretch and the masses of the rope and the pulley are negligible compared to the masses of the balls.

STRATEGY (Fill in the blanks.)

We draw free-body diagrams for the two balls and apply Newton’s Second Law to each. Since the rope does not stretch, the magnitudes of the balls’ accelerations are the same.

CALCULATION (Fill in the blanks.)

The net force in the \( x \)-direction is for \( M_1 \) is:

\[
\sum F_x = m_1a_x
\]

\[
\frac{\text{left}}{\text{right}} = ma_x
\]

The net force in the \( y \)-direction for \( M_2 \) is:

\[
\sum F_y = M_2a_y
\]

\[
\frac{\text{left}}{\text{right}} = ma_y
\]

3. The eqns in 1 and 2 above have two unknowns: \( a \) and \( T \). Combining these equations and eliminating tensions, gives

\[
a = \frac{a}{\frac{M_1 + M_2}{M_1 + M_2}}
\]

SELF-EXPLANATION PROMPTS

1. Explain in your own words why the magnitudes of the accelerations of the two balls are the same.

2. Why is the magnitude of the tension in the rope on the left side of the pulley the same as the magnitude on the right side of the pulley?

Optional Practice Problems: 5.18, 5.19, 5.20
Lesson 14: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 1300-kg car is rounding a curve on a flat horizontal roadway. The car is traveling at 13.4 m/s and slowing down at 2 m/s². The radius of the curve is 30 meters. The coefficient of static friction is μs = 0.80, and the coefficient of kinetic friction is μk = 0.40.

What is the net force of the car, magnitude and direction?

STRATEGY (Fill in the blanks.)

The car is slowing down which means it has a force directed opposite to its motion. Since this direction is tangent to the road, it is called the tangential force \( F_t \).

The car is also changing direction which means it has a radial force caused by friction between the tires and the road, \( F_c \). This force is directed towards the center of the curve.

The net force is the vector sum of \( F_t \) and \( F_c \).

CALCULATION (Fill in the blanks.)

1. Tangential force is \( F_t = ma_t = \underline{\ldots} \text{N} \).

2. Force of friction is \( F_c = ma_c = m\alpha = \underline{\ldots} \text{N} \)

3. Net force is \( F_{\text{net}} = \sqrt{\ldots + \ldots} = \underline{\ldots} \text{N} \)

The direction is ____________________________.

SELF-EXPLANATION PROMPTS

1. Why did we not need coefficient of friction for this problem?

2. What is the magnitude and direction of the net force if the car rounds the curve at constant speed?

Optional Practice Problems: 5.27, 5.37, 5.41
Lesson 15: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A man is pushing a 50-kg cart that accelerates at 1.3 m/s² on level ground where the coefficient of friction between the wheels and the ground is 0.03. How much resistance from the cart does he feel?

STRATEGY (Fill in the blanks.)

First, we apply Newton’s Second Law to determine the force needed to accelerate the cart. Then, we use Newton’s Third Law to determine the frictional force.

CALCULATION

The net force in the x-direction for the cart is:

\[ \sum F_x = ma_x \]

\[ \text{_____________________} = ma_x \]

The net force in the y-direction for the cart is:

\[ \sum F_y = ma_y \]

\[ \text{_____________________} = ma_y \]

The force exerted on the cart by the man = \[ _____________ \times _____________ = 79.7 \text{ N in the forward direction}. \]

The force exerted on the man by the cart = \[ _____________ \text{ in the _________ direction}. \]

SELF-EXPLANATION PROMPTS

1. Why don’t the force on the cart and the force on the man cancel out? That is, why does the mathematically correct statement, \(+79.7N - 79.7N = 0\), not imply that the net force in the above scenario is zero?

2. What type of frictional force acts on the cart: kinetic or static? Explain.

Optional Practice Problems: 5.29, 5.43, 5.49

Documentation Statement:
Lesson 18

Work with Constant and Varying Forces

Reading 6.1, 6.2
Examples 6.1 – 6.5
Homework Problems 6.18, 6.20, 6.52

- There is an optional Equation Dictionary entry in Appendix D for this lesson (1 PF pt).

Learning Objectives

[Obj 26] Explain the physics concept of work.
[Obj 27] Evaluate the work done by constant forces and by forces that vary with position.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A man drags a 50-kg crate 10 m across a rough horizontal surface, where the coefficient of kinetic friction, $\mu_k$, between the crate and the surface is 0.3. He pulls at constant speed and directs his pulling force 20° upward from the horizontal. How much work does he perform?

STRATEGY

Work done by a force is defined as the dot product of the applied force and the displacement: $W = \vec{F} \cdot \Delta \vec{x} = F \Delta x \cos \theta$, where $\theta$ is the angle between the direction of the force vector and the direction of the displacement vector.

To find the work done by the man, we find the force he applies to the crate, the displacement, and $\theta$, then compute the dot product between work and displacement.

IMPLEMENTATION

Since the crate is moving at constant speed, (acceleration is zero), the net force on the crate must be zero. The net force on the crate is the vector sum of the force applied by the man $\vec{F}_m$ and the force of kinetic friction $\vec{f}_k$.

Note that the force of friction depends on the direction of the man’s force because the man’s force affects the normal force (unless he pulls horizontally.)

The force of kinetic friction = (coefficient of friction) (normal force)

$$f_k = \mu (mg - F_m \sin \theta)$$

Since there is no acceleration, the x-component of $F_m$ must equal $f_k$. Thus,

$$F_m \cos \theta = \mu (mg - F_m \sin \theta)$$
Solving for $F_m$ we get

$$F_m = \frac{\mu mg}{\cos \theta + \mu \sin \theta}$$

The work done by $F_m$ is then

$$W = \vec{F}_m \cdot \Delta \vec{x} = F_m \Delta x \cos \theta$$

CALCULATION

$$W = \frac{\mu mg}{\cos \theta + \mu \sin \theta} \cos \theta \Delta x = 1325 \text{ J}$$

SELF-EXPLANATION PROMPTS

1. Start with the definition $W = \vec{F} \cdot \Delta \vec{x} = F \Delta x \cos \theta$ and explain how $W$ can be positive, negative, or zero.

2. Explain what it means to have (a) positive $W$ and (b) negative $W$.

3. In the example, you are told that the normal force is: $n = mg - F_m \sin \theta$. Describe the steps needed to obtain the normal force and then show the calculation.
Pre-Class Problem

STATEMENT OF THE PROBLEM

A crane lowers a 120-kg rock at constant speed through a vertical distance of 5 meters. How much work does the crane perform?

Answer: -5880 J
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. Solve for work $W$ and rank order from smallest (negative) to largest (positive) the work done in the following cases:

   - **Case A**
     \[ W_A = \]
   - **Case B**
     \[ W_B = \]
   - **Case C**
     \[ W_C = \]
   - **Case D**
     \[ W_D = \]

   Rank Order: Smallest (1) ____ (2) ____ (3) ____ (4) ____ Largest

3. Two identical objects are each displaced the same distance, one by a force $\vec{F}$ pushing in the direction of motion and the other by a force $2\vec{F}$ pushing at an angle $\theta$ relative to the direction of motion. The work done by the two forces is the same. What is the angle $\theta$? (Hint: See GOT IT? 6.1.)

   a) 0°
   b) 30°
   c) 45°
   d) 60°

4. CRITICAL THINKING: A weight lifter picks up a barbell and (1) lifts it chest high, (2) holds it for 30 seconds, and (3) puts it down slowly (but does not drop it). Rank order from smallest to largest the work $W$ the weight lifter performs during these three operations. Label the quantities as $W_1, W_2,$ and $W_3$. Justify your ranking order.
Homework Problems

6.18
Lesson 19

**Kinetic Energy and Power**

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**Learning Objectives**

[Obj 28] Explain the concept of kinetic energy and its relation to work.
[Obj 29] Explain the relation between energy and power.
[Obj 34] Solve problems by applying the work-energy theorem, conservation of mechanical energy, or conservation of energy.

**Notes**
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 3,000-kg sailboat is travelling at 25 m/s when a constant net force of 1200 N starts acting on it, in the direction of motion. What is the speed of the boat after it has travelled 200 m under the action of this force?

STRATEGY

When a force acts on a moving object, work is done on the object. The work done on the object results in the change of the object's kinetic energy $K$, defined as

$$K = \frac{1}{2}mv^2$$

where $m$ is the mass of the object and $v$ is its speed.

The net work done on the object and the change in the kinetic energy are related by the work-energy theorem

$$W_{net} = \Delta K = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

To find the answer to the question posed in the problem: 1. we find the net work done on the boat, 2. set it equal to the change in kinetic energy of the boat, and 3. solve the resulting equation for the unknown final speed.

IMPLEMENTATION

1. Net work: $W_{net} = \vec{F}_{net} \cdot \Delta \vec{x} = F_{net} \Delta x \cos \theta$

2. $\frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2 = W_{net}$

3. $v_f = \sqrt{\frac{2W_{net} + \frac{1}{2}m v_i^2}{m}}$
CALCULATION

\[ W_{net} = (1200 \text{ N})(200 \text{ m}) \cos 0^\circ = 240,000 \text{ Nm} = 240,000 \text{ J (joules)} \]

\[ v_f = \sqrt{\frac{480,000 \text{ J} + (3000 \text{ kg})(25 \frac{\text{ m}}{\text{s}^2})^2}{3000 \text{ kg}}} = 28 \frac{\text{ m}}{\text{s}} \]

SELF-EXPLANATION PROMPTS

1. State the work-energy theorem in your own words.

2. The work done by a constant force \( F \), acting along the direction of motion over a distance \( \Delta x \) equals \( F\Delta x \). From kinematics, we know that if an object starts from rest and accelerates with acceleration \( a \) over a distance \( \Delta x \), \( 2a\Delta x = v^2 \); and from Newton’s Second Law, we know that \( \vec{a} = \frac{F}{m} \). Combine the three equations and show that the work done by the force equals \( \frac{1}{2}mv^2 \).

3. Use the same procedure as above to show that the work done to increase the speed of mass \( m \) from \( v_1 \) to \( v_2 \) is equal to the change in its kinetic energy.
Pre-Class Problem

STATEMENT OF THE PROBLEM

Galileo is said to have dropped two objects of different mass from a tall tower to show that all objects fall with the same speed. If you drop two masses, \( m_1 \) and \( m_2 \), from the same height \( h \), do they reach the ground with the same kinetic energy?

Calculate the difference in their kinetic energies \( \Delta K \).

Answer:

\[ \Delta K = (m_1 - m_2)gh \]
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. Two cars, one four times as heavy as the other, are at rest on a frictionless horizontal track. Equal forces act on each of these cars for a distance of exactly 5 m. The kinetic energy of the lighter car will be _____ the kinetic energy of the heavier car.
   - a) one-quarter
   - b) one-half
   - c) equal to
   - d) twice
   - e) four times

4. Which of the following is true?
   - a) Neither $\Delta K$ nor $W_{\text{net}}$ can ever be negative.
   - b) $W_{\text{net}}$ can never be negative, but $\Delta K$ can be negative or positive.
   - c) $\Delta K$ can never be negative, but $W_{\text{net}}$ can be negative or positive.
   - d) $\Delta K$ and $W_{\text{net}}$ can be negative or positive.

5. CRITICAL THINKING: On Monday you run up the stairs to the top floor of a tall building. You run at a constant speed. On Tuesday you walk to the top, also at constant speed. On Wednesday you take a constant speed elevator. How do the amounts of work you did getting to the top of the building each day compare? How does the power compare?
Homework Problems

6.29
Lesson 20

Potential Energy

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Learning Objectives

[Obj 30] Explain the differences between conservative and nonconservative forces.
[Obj 31] Evaluate the work done by both conservative and nonconservative forces.
[Obj 32] Explain the concept of potential energy.
[Obj 33] Evaluate the potential energy associated with a conservative force.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM
A vertical spring with a spring constant \( k = 150 \text{ N/m} \) is compressed down 1.5 m. A 2-kg ball is placed on the compressed spring and released from rest. What height does the ball reach after it is released?

STRATEGY

This problem involves two examples of potential energy: the elastic energy of a compressed (or stretched) spring and the gravitational potential energy as an object moves from one elevation to another. An object is said to possess potential energy if, because of its condition, it can generate kinetic energy. A ball on a spring, for example, can be propelled by the force of the spring and gain kinetic energy. A ball can be dropped from a height and be propelled by the force of gravity and gain kinetic energy. Potential energy is traditionally denoted by the symbol \( U \).

The change in the elastic potential energy as a spring’s vertical extension changes from \( y_2 \) to \( y_1 \) is given by

\[ \Delta U_s = \frac{1}{2} ky_2^2 - \frac{1}{2} ky_1^2 \]

The change in the gravitational potential energy as an object of mass \( m \) moves from height \( y_2 \) to height \( y_3 \) is given by

\[ \Delta U_g = mgy_3 - mgy_2 \]

We solve the problem by comparing the energy imparted to the ball by the compressed spring to the energy lost by the ball as it climbs against the force of gravity. Symbolically

\[ \Delta U_s \Rightarrow \text{kinetic energy} \Rightarrow \Delta U_g \]

IMPLEMENTATION

\[ \frac{1}{2} ky_2^2 - \frac{1}{2} ky_1^2 = mg (y_3 - y_2) \]
CALCULATION

First, we are given the following quantities:

\[ y_1 = 0 \text{ m} \quad y_2 = -1.5 \text{ m} \quad k = 150 \text{ N/m} \]
\[ m = 2 \text{ kg} \quad g = 9.8 \text{ m/s}^2 \]

Let's set up a vertical coordinate axis with \( y_1 = 0 \) at the position of the unstretched spring. Now, we solve for \( y_3 - y_2 \) in

\[
\frac{1}{2}k y_2^2 - \frac{1}{2} k y_1^2 = mg (y_3 - y_2)
\]

\[ y_3 - y_2 = 8.6 \text{ m} \]

The ball rises 8.6 meters above the top of compressed spring.

SELF-EXPLANATION PROMPTS

1. The potential energy stored in a compressed spring comes from the work done by compressing the spring against its restoring force \( F = -ky \). Calculate that work and verify the above expression of the spring potential energy \( U_s \).

2. Do the same for the gravitational potential energy \( U_g \).

3. In solving the problem we ignored the mass of the spring. Including the mass of the spring is messy, but answering the following question is not. How would including the mass of the spring change the outcome of the calculation?
**Pre-Class Problem**

**STATEMENT OF THE PROBLEM**

A 2-kg ball is released from rest 3 meters above an unstretched spring of whose spring constant is 150 N/m. How much does it compress the spring before it comes to rest? (Before you start calculating, carefully draw the coordinate system and carefully identify all the relevant vertical coordinates. When you equate the two potential energy changes you will get a quadratic equation!)

**Answer:** 1 m

**Try it! (1 PF pt):** How high would the ball need to be released if you wanted to double the amount that the spring is compressed? Show your work.

**Documentation Statement:**
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. The energy stored in a compressed spring depends on the amount of compression. A given spring requires 10.0 J for a compression of 10.0 cm. How much total energy would be stored if it were compressed an additional 5.00 cm?
   a) 22.5 J
   b) 12.5 J
   c) 5.00 J
   d) 1.25 J
   e) Cannot be determined from the given information.

3. A trunk of mass \( m \) is lifted along a curved path of length \( L \) to a height \( h \). Another trunk with twice the mass is slid across a level floor \( (\mu_s = 0.5) \) along a curved path also having length \( L \). Which is greater, the work done against friction or the work done against gravity?
   a) More work is done against friction.
   b) More work is done against gravity.
   c) The work done against friction is the same as the work done against gravity.
   d) Cannot be determined from the given information.

4. CRITICAL THINKING: Why can't we define potential energy for friction? Explain.
### Homework Problems

7.14
7.42
Lesson 21

Conservation of Mechanical Energy

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- There is an optional *Equation Dictionary* entry in Appendix D for this lesson (1 PF pt).

Learning Objectives

[Obj 34] Solve problems by applying the work-energy theorem, conservation of mechanical energy, or conservation of energy.

[Obj 35] Describe the relation between force and potential energy using potential-energy curves.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

Note: Before working with this example, revisit Lesson 14, which has the same problem neglecting friction.

An amusement park ride consists of a vertical loop whose diameter is 15 m and a small 150-kg cart that runs on the inside track in the loop. The ride is designed to carry a maximum load of 320 kg.

If the cart is carrying its maximum load, how much kinetic energy must it have at the bottom of the loop if it is to negotiate the top of the loop safely (upside down) without leaving the track?

STRATEGY

In order not to leave the track at the top of the loop, the cart needs to go fast enough so that its weight provides the centripetal force necessary to just keep it on the track.

\[
\frac{mv_{\text{top}}^2}{R} = mg \text{ becomes } v_{\text{top}}^2 = gR
\]

As the cart climbs up the loop it loses kinetic energy and gains potential energy. The kinetic energies at the bottom and the top are related to the potential energies by

\[
KE_{\text{top}} + PE_{\text{top}} = KE_{\text{bottom}} + PE_{\text{bottom}}
\]

Since we know the minimal required kinetic energy at top, we can use the energy conservation equation to find KE at the bottom.
IMPLEMENTATION

\[ K_{top} = \frac{1}{2} mv_{top}^2 = \frac{1}{2} mgR \]

If we set the potential energy to be zero at the bottom of the track

\[ PE_{top} = mgh = 2mgR \]

The energy conservation equation then becomes

\[ \frac{1}{2} mgR + 2mgR = KE_{bottom} + 0 \]

CALCULATION

\[ KE_{bottom} = mg \left( \frac{1}{2} R + h \right) = mg \left( 2.5R \right) = 86,000 \text{ J} \]

SELF-EXPLANATION PROMPTS

1. State in your own words what we mean by “conservation principle.”

2. Why can the zero point of potential energy be chosen arbitrarily?

3. Sketch an energy bar chart (similar to those in Figure 7.8 in your textbook) for the cart at (a) the top of the track and (b) at the bottom of the track.

Documentation Statement:
Pre-Class Problem

STATEMENT OF THE PROBLEM

A 50-kg wrecker's ball is hanging on an 8-m rope that can support a maximum force of 1000 N. If the ball is swung in vertical circle, what is fastest speed it can have at the lowest point, such that the rope won't break?

Answer: 9 m/s
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. A bottle dropped from a balcony strikes the ground with a particular speed. To double the speed at impact, you would have to drop the bottle from a balcony that is
   a) twice as high.
   b) three times as high.
   c) four times as high.
   d) eight times as high.

3. A truck initially at rest at the top of a hill is allowed to roll down. At the bottom, its speed is 14 m/s. Next, the truck is again rolled down the hill, but this time it does not start from rest. It has an initial speed of 14 m/s at the top before it starts rolling down the hill. How fast is it going when it gets to the bottom?
   a) 14 m/s
   b) 17 m/s
   c) 20 m/s
   d) 24 m/s
   e) 28 m/s

4. CRITICAL THINKING: A skydiver whose parachute is fully deployed is descending at constant speed. Describe what is happening to her kinetic energy, her potential energy and her total mechanical energy as she falls. Is any work being done? If yes, where does it go?
Homework Problems

7.24
7.55
Lesson 22

Lab 4- Conservation of Energy

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- There is a LAB this lesson.

Learning Objectives

[Obj 34] Solve problems by applying the work-energy theorem, conservation of mechanical energy, or conservation of energy.

Notes
Pre-Lab Questions

In this lab, a spring is compressed a distance $x$ and used to launch a cart of mass $M$ along a perfectly horizontal air track. The speed of the cart, $v$, is measured some distance down the air track and used to calculate the spring constant, $k$ (refer to the lab handout and Example 7.4 in the textbook).

1. Use the principle of conservation of mechanical energy to find an expression for the speed of the cart as a function of the compression distance.

   a) $v = \frac{k}{M} x$
   b) $v = \sqrt{\frac{k}{M}} x$
   c) $v = \frac{k}{M} x - 2gh$
   d) $v = \sqrt{\frac{k}{M}} x^2 - 2gh$

2. When graphing the data in Part II, you are asked to plot $v$ vs. $x$. Describe the shape of the plot and explain why it makes sense to plot the data in such a way.

3. After plotting $v$ vs. $x$, your group determines that the slope of the best-fit line through the data points is 50 s$^{-1}$. If the air cart has a mass of 0.50 kg, the spring constant $k$ is

   a) 25 N/m
   b) 50 N/m
   c) 1250 N/m
   d) Cannot be determined with the given information.
Homework Problems

7.56
Lesson 23

Orbital Motion

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- There is an optional *Equation Dictionary* entry in Appendix D for this lesson (1 PF pt).

Learning Objectives

[Obj 36] Explain the concept of universal gravitation.
[Obj 37] Solve problems involving the gravitational force between two objects.
[Obj 38] Determine the speed, acceleration, and period of an object in circular orbit.

Notes
**Worked Example**

Study the given problem and solution, then answer the questions regarding the problem.

**STATEMENT OF THE PROBLEM**

A spacecraft is orbiting 200 km above the surface of the planet Mars. One of the astronauts on board drops a pen. How fast does the pen fall relative to the surface of Mars? How fast does the pen fall relative to the rest of the spacecraft?

**STRATEGY**

The spacecraft is in orbit about Mars, meaning that it is traveling in a circular path 200 km above the surface of Mars. Since the orbit is circular, the motion of the spacecraft (and everything on board it including the pen) is undergoing centripetal motion; the acceleration is therefore centripetal acceleration.

**IMPLEMENTATION**

1. What is the orbital radius of the spacecraft?
2. What is the gravitational force?

By combining the gravitational force with Newton’s Second Law, we can find the acceleration of the spacecraft and everything on board.

**CALCULATION**

1. \( r_{\text{orbit}} = r_{\text{Mars}} + h_{\text{orbit}} = 3,389 \text{ km} + 200 \text{ km} = 3589 \text{ km} \)
2. Combining the gravitational force, \( F_{\text{gravitational}} = \frac{GM_{\text{spacecraft}}M_{\text{Mars}}}{r_{\text{orbit}}^2} \); with Newton’s Second law, \( \vec{F}_{\text{net}} = m\vec{a} \), we find the magnitude acceleration, \( a = \frac{GM_{\text{Mars}}}{r_{\text{orbit}}} = \frac{3.32}{s^2} \).

The entire spacecraft and everything inside is accelerating at the same rate, so the pen will not appear to fall.
SELF-EXPLANATION PROMPTS

1. Which direction is the spacecraft accelerating and to which objects does the value of acceleration, $a = 3.32 \frac{m}{s^2}$, apply?

2. How is the quantity "$r$" defined in the equation for universal gravitation? Use your definition to justify why $r_{\text{orbit}} = r_{\text{Mars}} + h_{\text{orbit}}$ in the example.

3. If the pen is accelerating, explain why it is considered to be in "free fall".
Pre-Class Problem

STATEMENT OF THE PROBLEM

It is commonly believed that you experience a brief feeling of weightlessness when you are riding an elevator. Consider an elevator which has a final speed of 2.3 m/s. In order for you to experience a feeling of “weightless”, how long must it take the elevator to go from rest to its final speed (assuming constant acceleration)? Does this happen when the elevator is going up or going down?

Free-Body Diagram (required)

Answer: 0.23 s, going down
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. What is the approximate force that the Moon exerts on you when it is directly overhead? (Hint: You will need data from Appendix E to answer this question)
   
   a) $2 \times 10^{-4}$ N  
   b) $2 \times 10^{-3}$ N  
   c) $2 \times 10^{-2}$ N  
   d) $2 \times 10^{-1}$ N  
   e) 2 N

3. The magnitude of the force of gravity between two identical objects is $F_0$. If the mass of each object and the distance are doubled, what is the new force of gravity between the objects?
   
   a) $F_0$  
   b) $4F_0$  
   c) $8F_0$  
   d) $\frac{1}{2}F_0$  
   e) $\frac{1}{4}F_0$

4. CRITICAL THINKING: A geosynchronous orbit is one where the orbital object stays basically over the same place on earth all the time. The object stays relatively motionless in the sky above. The mass of Earth is $5.97 \times 10^{24}$ kg, and the period is the same as that of Earth at $T = 23$ hr, 56 min, 4 sec. Describe how you would determine the altitude for geosynchronous orbit. (Hint: How are orbital period $T$ and orbital radius related?)
Homework Problems

8.17
Lesson 24

Gravitational Energy

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Learning Objectives

[Obj 39] Solve problems involving changes in gravitational potential energy over large distances.
[Obj 40] Use the concept of mechanical energy to explain open and closed orbits and escape speed.
[Obj 41] Use conservation of mechanical energy to solve problems involving orbital motion.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 120-kg satellite is in a circular orbit 100 km above the surface of the Earth. How would the total energy of the satellite change if it were moved to a higher orbit 200 km above the surface of the Earth?

STRATEGY

The total energy (potential and kinetic) of a satellite in a circular orbit about the Earth is

\[ E = -\frac{1}{2} \frac{GMm}{r} \]

where \( G = 6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2 \) is the universal gravitational constant
\( m \) is the mass of the satellite
\( M \) is the mass of the Earth = \( 5.97 \times 10^{24} \text{ kg} \)
\( r \) is the radius of the orbit (radius of the Earth + altitude)

IMPLEMENTATION

We will calculate the energy in each of the two orbits and subtract to get the change in energy between the orbits.

\[ \Delta E = -\frac{1}{2} \frac{GMm}{r_{final}} - \left( -\frac{1}{2} \frac{GMm}{r_{initial}} \right) = \frac{1}{2} GMm \left( \frac{1}{r_{initial}} - \frac{1}{r_{final}} \right) \]

CALCULATION

\[ r_{initial} = 6.37 \times 10^6 + 100 \times 10^3 = 6.47 \times 10^6 \text{ m} \]
\[ r_{final} = 6.37 \times 10^6 + 200 \times 10^3 = 6.57 \times 10^6 \text{ m} \]

\[ \Delta E = \frac{1}{2} (6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2)(5.97 \times 10^{24} \text{ kg})(120 \text{ kg}) \left( \frac{1}{6.47 \times 10^6 \text{ m}} - \frac{1}{6.57 \times 10^6 \text{ m}} \right) \]

\[ \Delta E = 3600 \times 10^6 \text{ J} \]
SELF-EXPLANATION PROMPTS

1. How is the gravitational energy formula derived? Look in the text and summarize the steps for this derivation.

2. The gravitational energy equation includes gravitational potential energy. Where is the gravitational potential energy zero?

3. Explain why is the total energy negative.
Pre-Class Problem

STATEMENT OF THE PROBLEM

A 1200-kg satellite is in an elliptical orbit around the Earth. At perigee, the altitude of the satellite is 1,000 km above the surface, and at apogee the altitude is 10,000 km above the surface.

If the satellite is traveling at 8.6 km/s at perigee, what is its speed at apogee?

Answer: 3.89 m/s

Try it! (1PF pt): Determine the total energy (kinetic + potential) of the satellite at both perigee and apogee. Show your work.

Documentation Statement:
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. Consider a spacecraft orbiting the Sun in a circular orbit. The spacecraft fires its engines adding energy until it escapes the Sun’s gravity.

   Compare the total energy $E$ for the circular orbit $A$, elliptical orbit $B$, and parabolic trajectory $C$.

   a) $E_A < E_B < E_C$
   b) $E_A = E_B = E_C$
   c) $E_A > E_B > E_C$

3. Suppose an object is moving along any one of the given orbital paths. What is true regarding the orbits depicted?

   a) The kinetic energy is constant in all the orbits, while the potential energy changes with distance from the Sun.
   b) The potential energy is constant for all points in any one of the orbits.
   c) Total energy decreases from the circular orbit $A$ until it equals zero for the parabolic trajectory $C$.
   d) Total energy is constant for any point along any one of the orbits.

4. CRITICAL THINKING: A physics book claims that, “Moon-bound spacecraft have speeds just under $v_{esc}$, so that if anything goes wrong (as with Apollo 13), they will return to Earth.” Explain why this statement is correct or incorrect. Think about the derivation of the escape velocity equation and whether a spacecraft can get to the Moon without escaping the Earth.
Homework Problems

8.27
MP
Lesson 25

Critical Thinking: Orbital Energies

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- There is an EXAM-PREP QUIZ this lesson.

Learning Objectives

[Obj 39] Solve problems involving changes in gravitational potential energy over large distances.

[Obj 40] Use the concept of mechanical energy to explain open and closed orbits and escape speed.

Notes
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. The total energy of a satellite in a particular bound orbit
   a) varies depending on the satellite’s position in that orbit.
   b) is always positive.
   c) is always negative.
   d) is always exactly zero.

3. For two objects separated by a distance \( r \), the magnitude of the gravitational potential energy is \( U_0 \). If the distance is doubled, what is the new gravitational potential energy?
   
   a) \( U_0 \)  
   b) \( 4U_0 \)  
   c) \( 8U_0 \)  
   d) \( \frac{1}{2}U_0 \)  
   e) \( \frac{1}{4}U_0 \)

4. CRITICAL THINKING: The International Space Station (ISS) (http://www.nasa.gov/mission_pages/station/main/index.html) orbits Earth at an altitude of 350 km. Since the station and the astronauts inside are in free fall together, they float around inside the ISS modules. If the station were stationary at that altitude, how would the astronauts’ weights compare to their weights at the surface of Earth?
Homework Problems

MP
8.61
Lesson 26

Center of Mass

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Learning Objectives

[Obj 42] Calculate the center of mass for systems of discrete particles and for continuous mass distributions.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

Four small masses \( m_1, m_2, m_3, \) and \( m_4 \) are tied together with rigid rods so that they form a square of side 1 m, as shown in the figure. We want to write Newton’s Second Law for the entire system as if all the mass were concentrated at a single point, that is \( \vec{F}_{\text{net}} = (m_1 + m_2 + m_3 + m_4) \vec{a} \), where \( \vec{F}_{\text{net}} \) is the net external force on the system (i.e. the vector sum of all the external forces) and \( \vec{a} \) is the acceleration of the system. What is the location of such a point? Consider the mass of the connecting rods to be very small compared to the masses on the corners.

STRATEGY

The point described above is called the center-of-mass of the system. Under the action of external forces the assembly of the masses moves as if it were a single mass. For example, in projectile motion the center of mass of the four masses will follow a parabola.

The location \( \vec{r} \) of the center of mass point is given by

\[
\vec{r}_{\text{CM}} = \frac{m_1 \vec{r}_1 + m_2 \vec{r}_2 + \ldots}{(m_1 + m_2 + \ldots)}
\]

IMPLEMENTATION

We choose a coordinate system for the assembly of the four masses and apply the center-of-mass equation. Any coordinate system will work. We choose the origin of our system to be the center of the square.
CALCULATION

\[ x_{CM} = \frac{1 \text{ kg} (-0.5 \text{ m}) + 1 \text{ kg} (+0.5 \text{ m}) + 2 \text{ kg} (-0.5 \text{ m}) + 2 \text{ kg} (+0.5 \text{ m})}{6 \text{ kg}} = 0 \]

\[ y_{CM} = \frac{1 \text{ kg} (+0.5 \text{ m}) + 1 \text{ kg} (+0.5 \text{ m}) + 2 \text{ kg} (-0.5 \text{ m}) + 2 \text{ kg} (-0.5 \text{ m})}{6 \text{ kg}} = -\frac{1}{6} \text{ m} \]

The center of mass is 1/6 meters under the origin on the y-axis.

SELF-EXPLANATION PROMPTS

1. Intuitively, the center of mass can be thought of as the point at which the assembly could be stably supported. Using this approach, where would you expect the center of mass of the two 1-kg masses to be?

2. What about the center of mass of the two 2-kg masses?

3. Justify, using symmetry, why the center of mass is on the y-axis and below the x-axis?
Pre-Class Problem

STATEMENT OF THE PROBLEM

Find the location of the center-of-mass of a system comprised of three 1-kg masses located at three corners of a square whose side is 1 m. (Hint: Draw a picture and mark the center-of-mass.)

Answer: $x = -0.17$ m, $y = -0.17$ m in a coordinate system with the origin at the center of the square.
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. (True/False) A 4.8 ton elephant is standing in a 15 ton railcar that is at rest on a frictionless track. The elephant begins to walk towards the other end of the car. For every meter the elephant moves, the car moves 1 meter in the opposite direction.
   
   a) True
   b) False

3. (True/False) According to the equations of motion for a projectile, a firecracker follows a parabolic path, neglecting air resistance. After it explodes, the center of mass of the pieces still follows a parabolic trajectory.
   
   a) True
   b) False

4. CRITICAL THINKING: A fully-loaded canoe is attached to an empty canoe with a bungee cord. The canoes are at rest on a placid lake. A passenger in the heavier canoe pushes the canoes apart, stretching the bungee cord. Describe what happens to the center of mass of the system and explain your reasoning.
Homework Problems

9.16
9.89
Lesson 27

Conservation of Linear Momentum & Collisions

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Learning Objectives

[Obj 43] Explain the concept of linear momentum of a system of particles and express Newton's second law of motion in terms of the linear momentum of the system.

[Obj 44] Explain the law of conservation of linear momentum and the condition under which it applies.

[Obj 45] Apply conservation of linear momentum to solve problems involving systems of particles.

[Obj 46] Explain the concept of impulse and its relation to force.

[Obj 47] Explain the differences between elastic, inelastic, and totally inelastic collisions.

[Obj 48] Apply appropriate conservation laws to solve problems involving collisions in one- and two-dimensions.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 1-kg ball, $m_1$, collides with a 3-kg ball, $m_2$, as shown. The balls have initial velocities of $v_{1\text{ initial}} = 3 \text{ m/s}$ and $v_{2\text{ initial}} = -3 \text{ m/s}$. Immediately after the collision $v_2\text{ final} = 2 \text{ m/s}$, what is $v_{1\text{ final}}$?

STRATEGY

This is a one-dimensional Conservation of Linear Momentum problem. To use the concept of conservation of momentum, we must ensure that there is no net external force acting on the system. Since 1) we are only interested in what happens immediately before and after the collision, and 2) the collision is brief, we can assume that any external forces acting on the balls are negligible. Because of these conditions, we say that linear momentum is conserved in collisions. (Note that linear momentum can be conserved during other interactions as long as the condition of no net external forces is met.) The Conservation of Linear Momentum equation is $\sum m v_{\text{initial}} = \sum m v_{\text{final}}$, and, specific to this problem, $m_1 v_{1\text{ initial}} + m_2 v_{2\text{ initial}} = m_1 v_{1\text{ final}} + m_2 v_{2\text{ final}}$. As the figure shows it is possible for one of the balls to have a negative velocity (oppositely directed) after or prior to the collision.

IMPLEMENTATION

We will designate a standard $x$-$y$ coordinate system as shown. We will use the conservation of linear momentum equation and solve it for $v_{1\text{ final}}$.
CALCULATION

Starting with: \( m_1 v_{1\text{ initial}} + m_2 v_{2\text{ initial}} = m_1 v_{1\text{ final}} + m_2 v_{2\text{ final}} \)

It becomes:
\[
\frac{m_1 v_{1\text{ initial}} + m_2 v_{2\text{ initial}} - m_2 v_{2\text{ final}}}{m_1} = v_{1\text{ final}}
\]

Now substituting:
\[
\frac{(1 \text{ kg}) \left( 3 \text{ m/s} \right) + (3 \text{ kg}) \left( -3 \text{ m/s} \right) - (3 \text{ kg}) \left( 2 \text{ m/s} \right)}{3 \text{ kg}} = v_{1\text{ final}}
\]

\[ v_{1\text{ final}} = -4 \text{ m/s} \]

SELF-EXPLANATION PROMPTS

1. Why is it important to ensure that no net external force acts on the objects?

2. Why can you not use the absolute values of the velocities in the above calculations?

3. Using the calculated final velocity of ball 1, show that linear momentum was indeed conserved in the collision.
Pre-Class Problem

The diagram on the left shows a collision between a series of railroad cars. If the cars, each having a mass of 3000 kg, depart the collisions as one coupled group, what will be the final velocity of the assembly?

Answer: 2.5 m/s
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. Linear momentum of a system is conserved if
   a) the net external force is zero.
   b) the energy of the system is conserved.
   c) the net work done is positive.
   d) only conservative forces are doing work.

3. A 500-g firework rocket is moving at 60 m/s straight upward when it explodes. The sum of all the momentum vectors of the rocket fragments immediately after the explosion is
   a) zero.
   b) 30 kg m/s straight up.
   c) 30 kg m/s in multiple directions.
   d) more than 30 kg m/s because of the energy added by the explosion.

4. CRITICAL THINKING: Consider a rubber bullet and an aluminum bullet; both have the same size, speed and mass. Each bullet is fired at a block of wood. The rubber bullet bounces back, the aluminum bullet penetrates the block. Which is most likely to knock the block over? Explain.
Homework Problems

9.38
Lesson 28

Lab 5 – 1-D Collisions

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- There is a LAB this lesson.

Learning Objectives

[Obj 46] Explain the concept of impulse and its relation to force.
[Obj 47] Explain the differences between elastic, inelastic, and totally inelastic collisions.
[Obj 48] Apply appropriate conservation laws to solve problems involving collisions in one- and two-dimensions.

Notes

Documentation Statement:
Journal Questions

1. Briefly describe the purpose and goals of this lab. (One to two complete sentences)

2. In Part I of the lab, a heavy cart (mass $m_1$) and a stationary light cart (mass $m_2$) will undergo a one-dimensional collision on a frictionless air track. Assuming the collision is elastic, write the expression for the final velocity of cart 2, $v_{2f}$, in terms of the initial velocity of cart 1, $v_{1i}$.

3. In Part II of the lab, a heavy cart (mass $m_1$) and a stationary light cart (mass $m_2$) will undergo a totally inelastic one-dimensional collision on a frictionless air track. Derive a similar expression for the final velocity of the joined carts (masses $m_1 + m_2$), $v_f$, in terms of the initial velocity of cart 1, $v_{1i}$, starting from the equation for conservation of momentum.

4. Suppose you make a plot of the final velocity of cart 2, $v_{2f}$, versus the initial velocity of cart 1, $v_{1i}$, for the elastic collision. What would the plot look like? Write an expression, in terms of $m_1$ and $m_2$, for the slope associated with this plot.

5. If you plotted the final velocity of the joined carts, $v_f$, versus the initial velocity of cart 1, $v_{1i}$, for the totally inelastic collision instead, how would the slope for the totally inelastic collision compare to the slope for the elastic collision? Explain.
Lesson 28

Homework Problems

9.28
9.61
Lesson 29

Collisions and Conservation of Energy:
Where does the Energy Go?

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Learning Objectives

[Obj 46] Explain the concept of impulse and its relation to force.
[Obj 47] Explain the differences between elastic, inelastic, and totally inelastic collisions.
[Obj 48] Apply appropriate conservation laws to solve problems involving collisions in one- and two-dimensions.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 1.0-kg puck (puck 1) is sliding at 45° above the x-axis with a speed of 1.0 m/s. Another 1.0-kg puck (puck 2) is sliding with a speed of 0.50 m/s at 45° below the x-axis. The pucks collide, and puck 2 flies off at 45° below the x-axis, at 0.80 m/s.

a) What is the velocity of puck 1 after the collision?

b) Was this collision elastic?

STRATEGY

Since total linear momentum \( \vec{p} = \sum m \vec{v} \) is conserved in any collision, we can use the conservation of linear momentum to obtain the set of equations we need to solve for the velocity of puck 1. We can then compare the kinetic energies before and after the collision. If the kinetic energies before and after the collision are the same (conserved), the collision was elastic.

IMPLEMENTATION

Since total momentum is conserved we have:

\[
m_1 \vec{v}_{1i} + m_2 \vec{v}_{2i} = m_1 \vec{v}_{1f} + m_2 \vec{v}_{2f}
\]

Writing this expression in terms of x- and y-components gives us two equations with two unknowns – the magnitude and direction of the velocity of the first puck – which we will solve. To see if the collision was elastic we compare the kinetic energies before and after the collision:

\[
\frac{1}{2} m_1 v_{1i}^2 + \frac{1}{2} m_2 v_{2i}^2 = \frac{1}{2} m_1 v_{1f}^2 + \frac{1}{2} m_2 v_{2f}^2
\]
CALCULATION

a) Before the collision, the x- and y- components of the total momentum are:

\[ p_{xi} = (1.0 \text{ kg})(1.0 \frac{m}{s} \cdot \cos 45^\circ) + (1.0 \text{ kg})(0.50 \frac{m}{s} \cdot \cos 45^\circ) = 1.06 \frac{\text{kg} \cdot \text{m}}{\text{s}} \]

\[ p_{yi} = -(1.0 \text{ kg})(1.0 \frac{m}{s} \cdot \sin 45^\circ) + (1.0 \text{ kg})(0.50 \frac{m}{s} \cdot \sin 45^\circ) = -0.354 \frac{\text{kg} \cdot \text{m}}{\text{s}} \]

and after collision they are:

\[ p_{xf} = (1.0 \text{ kg})(v_{1fx}) + (1.0 \text{ kg})(0.80 \frac{m}{s} \cdot \cos 45^\circ) = 1.06 \frac{\text{kg} \cdot \text{m}}{\text{s}} \]

\[ p_{yf} = (1.0 \text{ kg})(v_{1fy}) - (1.0 \text{ kg})(0.80 \frac{m}{s} \cdot \sin 45^\circ) = -0.354 \frac{\text{kg} \cdot \text{m}}{\text{s}} \]

Solving for the speed of the puck 1 and the direction angle \( \theta \) we get: \( v_{1f} = 0.54 \frac{m}{s} \) and \( \theta = 23^\circ \), above the positive x-axis.

b) Calculating the total kinetic energy of the two pucks before the collision, we get 0.62 J; after the collision the kinetic energy is 0.46 J. The collision was not elastic, but it was not totally inelastic.

SELF-EXPLANATION PROMPTS

1. Solve the momentum equations for the speed and direction of motion of puck 1 (i.e., fill in the steps omitted above).

2. Calculate the total kinetic energy of the two pucks before and after the collision (i.e., fill in the steps omitted above), and confirm that the collision is inelastic.

3. Where did the energy go during the inelastic collision?
Pre-Class Problem

Two masses, \( m_1 \) and \( m_2 \), move at right angles, meet at the origin and fly off, sticking together. Their initial speeds are the same. If \( m_1 = 3 \, m_2 \), what are their speed and direction after collision?

Answer: 0.79\( v \), 18.4°
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. If the net external force acting on an object is constant, what is true about its momentum $\vec{p}$?

   a) The magnitude and direction of $\vec{p}$ may change.
   b) The magnitude of $\vec{p}$ remains constant but the direction may change.
   c) The magnitude of $\vec{p}$ may change but the direction remains constant.
   d) The magnitude and direction of $\vec{p}$ remain constant.

3. Match the diagram to the type of collision between objects of equal mass.

   ![Diagrams]

   Case A  Case B  Case C  Case D

   ___ Elastic collision
   ___ Inelastic collision
   ___ Totally inelastic collision

4. CRITICAL THINKING: Bird strikes are a significant flight safety hazard. Consider an F-16 bird strike where a goose impacts the canopy. The F-16 canopy deforms during the collision and the bird parts deflect away from the aircraft. What type of collision is this? Explain.
Homework Problems

MP
9.78
Lesson 30

GRADED REVIEW 3

Learning Objectives

[Obj 26] Explain the physics concept of work.
[Obj 27] Evaluate the work done by constant forces and by forces that vary with position.
[Obj 28] Explain the concept of kinetic energy and its relation to work.
[Obj 29] Explain the relation between energy and power.
[Obj 30] Explain the differences between conservative and nonconservative forces.
[Obj 31] Evaluate the work done by both conservative and nonconservative forces.
[Obj 32] Explain the concept of potential energy.
[Obj 33] Evaluate the potential energy associated with a conservative force.
[Obj 34] Solve problems by applying the work-energy theorem, conservation of mechanical energy, or conservation of energy.
[Obj 35] Describe the relation between force and potential energy using potential-energy curves.
[Obj 36] Explain the concept of universal gravitation.
[Obj 37] Solve problems involving the gravitational force between two objects.
[Obj 38] Determine the speed, acceleration, and period of an object in circular orbit.
[Obj 39] Solve problems involving changes in gravitational potential energy over large distances.
[Obj 40] Use the concept of mechanical energy to explain open and closed orbits and escape speed.
[Obj 41] Use conservation of mechanical energy to solve problems involving orbital motion.
[Obj 42] Calculate the center of mass for systems of discrete particles and for continuous mass distributions.
[Obj 43] Explain the concept of linear momentum of a system of particles and express Newton's second law of motion in terms of the linear momentum of the system.
[Obj 44] Explain the law of conservation of linear momentum and the condition under which it applies.
[Obj 45] Apply conservation of linear momentum to solve problems involving systems of particles.
[Obj 46] Explain the concept of impulse and its relation to force.
[Obj 47] Explain the differences between elastic, inelastic, and totally inelastic collisions.
[Obj 48] Apply appropriate conservation laws to solve problems involving collisions in one- and two-dimensions.

Notes
Lesson 18: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A man drags a 50-kg crate 10 m across a rough horizontal surface, where the coefficient of friction between the crate and surface is 0.3. He pulls at a constant speed and he directs his pulling force 20° downward from the horizontal. How much work does he perform?

STRATEGY (Fill in the blanks.)

The strategy is the same as used for the worked example in Lesson 18, the only difference is that the force of friction is now

\[ f_k = \mu (mg + F_m \sin \theta) \]

The force exerted by the man is now

\[ F_m = \frac{\mu mg}{\cos \theta + \mu \sin \theta} \]

CALCULATION (Fill in the blanks.)

\[ W = \frac{\mu mg}{\cos \theta + \mu \sin \theta} \cos \theta \Delta x = 1328 \text{ J} \]

SELF-EXPLANATION PROMPTS

1. The work done in this case is 3 J more than in the worked example for Lesson 18. Explain why the work increased.

2. What work does friction do?

3. How would the answer change if the surface was frictionless instead?

Optional Practice Problems: 6.13, 6.19, 6.21
Lesson 19: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 1500-kg car is travelling at 26.8 m/s. The driver applies a small braking force of 800 N. How far does the car travel before it slows down to 13.4 m/s?

STRATEGY (Fill in the blanks.)

Apply the ______________ theorem and solve the resulting equation for the unknown displacement.

CALCULATION (Fill in the blanks.)

\[ W_{net} = F \cdot \Delta x = \underline{\underline{}} - \underline{\underline{}} \]

\[ \Delta x = \underline{\underline{}} = \frac{134670 \text{ J}}{-800 \text{ N}} = 505 \text{ m} \]

SELF-EXPLANATION PROMPTS

1. What happens to the stopping distance if the speed of the car is doubled, assuming the same braking force?

2. Where does the “braking force” come from?

Optional Practice Problems: 6.27, 6.39
Lesson 20: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

An object of mass $m$ is released at rest from a height $h$ above ground. What is the speed of the object just before it reaches the ground?

STRATEGY (Fill in the blanks.)

The object has positive potential energy relative to the ground. As it falls, that energy gets converted into kinetic. Symbolically,

$$\Delta U_g \Rightarrow \underline{\text{_________}}$$

CALCULATION (Fill in the blanks.)

$$\underline{\text{_________}} = \frac{1}{2} mv^2$$

Setting the kinetic energy equal to $\Delta U_g$ and solving for the speed $v$ we get

$$v = \sqrt{2gh}$$

SELF-EXPLANATION PROMPTS

1. Why is there no mass $m$ in the final answer? Review the calculation and show where the mass drops out.

2. Does the fact that there is no mass $m$ in the final answer tell us that the gravitational potential energy does not depend on the mass?

3. This problem can also be solved using 1-D kinematics. Use this method and compare the results.

Optional Practice Problems: 7.13, 7.17, 7.30
Lesson 21: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 60-kg skier starts from rest and skis down a zig-zag trail. When she reaches the bottom of the trail she has descended a vertical elevation of 600 m. If she loses 12% of her energy to friction, what is her speed at the bottom of the trail?

STRATEGY (Fill in the blanks.)

We apply a modified energy conservation equation, accounting for the energy lost to friction

\[ KE_{bottom} = 0.88(KE_{top} + PE_{top}) \]

And taking PE to be zero at the bottom of the trail.

CALCULATION (Fill in the blanks.)

\[ KE_{top} = \text{__________} \quad PE_{top} = \text{__________} \]
\[ KE_{bottom} = 310,464 \text{ J} \]
\[ v_{bottom} = \text{__________} \]
\[ v_{bottom} = 101 \text{ m/s} \]

SELF-EXPLANATION PROMPTS

1. In your own words describe the modified conservation equation we used.

2. Why does the contour of the terrain not matter in this calculation?

3. How would the problem need to be changed so that we could use the force of friction formula, \( \vec{f} = \mu \vec{n} \)?

Optional Practice Problems: 7.19, 7.53, 7.57

Documentation Statement:
Lesson 23: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

Many movies contain scenes where the actors experience weightlessness. These scenes are usually filmed in an airplane that is undergoing carefully choreographed maneuvers which simulate weightlessness. Consider the following flight path: From the start of the maneuver to $t=120$ s, the airplane’s height is described by $y = 225t$. During the next part of the maneuver, which lasts 60 seconds, the airplanes height is given by $y = -4.9t^2 - 1176t - 43560$. For the final 15 seconds of the maneuver, the airplane’s altitude is given by $y = t^2 - 23000$. During what time period is the airplane “weightless”?

STRATEGY (Fill in the blanks.)

The back of the airplane will appear to be weightless (aka “free fall”) when the airplane accelerates at same rate as all the objects in the plane. We will use the derivative to find the times when the acceleration is 9.8 m/s$^2$.

CALCULATION

1. During the first part of the maneuver, we take the derivative of position to find the velocity, which is ________. By taking the derivative of velocity, we find the acceleration to be 0 m/s$^2$. The plane is not in free fall.

2. During the second part of the maneuver, find that the velocity is given by ________. We take the derivative of velocity to find that the acceleration is given by ________. The plane is therefore in free fall.

3. During the third part of the maneuver, we find that the velocity is _______ and the acceleration is ________. The plane is not in free fall.

SELF-EXPLANATION PROMPTS

1. What part of the position equation determines the plane is free fall in the 2nd part of the maneuver? What parts of the equation does not matter?

2. How could you modify the position equation for the third part of the maneuver to make the plane be in free fall?

Optional Practice Problems: 8.35, 8.19,
Lesson 24: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

If a 300-kg satellite, in a circular orbit 150 km above the surface of the Earth crashes to the ground (or burns up), how much energy is lost?

STRATEGY (Fill in the blanks.)

The total energy (potential and kinetic) of a satellite in a circular orbit about the Earth is

\[ E = -\frac{1}{2} \frac{GMm}{r} \]

where \( G = 6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2 \) is the universal gravitational constant

\( m \) is the mass of the satellite

\( M \) is the mass of the Earth = 5.97 \( \times 10^{24} \) kg

\( r \) is the radius of the orbit, i.e. radius of the Earth + altitude

CALCULATION (Fill in the blanks.)

\[ \Delta E = \frac{1}{2} GMm \left( \frac{1}{r_{\text{initial}}} - \frac{1}{r_{\text{final}}} \right) \]

\[ r_{\text{initial}} = 6.37 \times 10^6 + 150 \times 10^3 = 6.52 \times 10^6 \text{ m} \]

\[ r_{\text{final}} = \]

\[ E_{\text{lost}} = 216 \times 10^6 \text{ J} \]

SELF-EXPLANATION PROMPTS

1. The gravitational energy equation includes the gravitational potential energy. Where is the gravitational potential energy zero?

2. Complete the calculation.

Optional Practice Problems: 8.30, 8.58

Documentation Statement:
Lesson 26: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

Where is the center of mass of a 2-m barbell with a 1-kg mass on the left and a 3-kg mass on the right? Consider the mass of the bar to be very small (negligible) compared to the masses on the corners.

1kg

2 m

3kg

STRATEGY (Fill in the blanks.)

Choose a coordinate system with the origin at the center of the bar.

Apply the center-of-mass equation and solve for the x-coordinate.

CALCULATION (Fill in the blanks.)

\[ x_{CM} = \frac{1 \text{ kg } (\_\_\_\_) + 3 \text{ kg } (\_\_\_\_)}{1 \text{ kg } + 3 \text{ kg}} = 0.5 \text{ m} \]

SELF-EXPLANATION PROMPTS

1. Does the result agree with your intuition?

2. Convince yourself that the choice of the coordinate system does not matter. Choose the origin of the coordinate system at the left end, at the location of the 1 kg mass, and show that you get the same result. (Draw a diagram and mark the location of the center-of-mass as calculated originally and again as calculated using the new coordinate system.)

Optional Practice Problems: 9.12, 9.38, 9.49
Lesson 27: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 100-kg clown is launched from a 500-kg circus cannon. After the firing of Bozo, he has a speed of 15 m/s. Assuming that his shoes and costume are so highly polished that there is no friction as he moves out of the cannon barrel and that the cannon and clown initially are at rest, what is the final velocity of the cannon?

STRATEGY (Fill in the blanks.)

We will use a standard x-y orientation for this ______ dimensional problem involving conservation of linear __________. The statement “that there is no friction” allows us to meet the condition of no _____ _____ acting on the objects during the event. The event in which momentum is conserved in this case is an explosion where the cannon and the clown are considered initially as ______ stationary object that then becomes two objects with individual ______. We will start with the Conservation of Momentum relation and solve for the ________________.

CALCULATION (Fill in the blanks.)

First: \( \sum m v_{\text{initial}} = \sum \) ______

Now: \( (m_{\text{cannon}} + \) ____\() v_{\text{initial}} = \) _____ \( v_{\text{cannon final}} - \) \( m_{\text{clown}} v_{\text{clown final}} \)

With numbers: \( (\) ____ + 100 kg \( \) ____ m/s \( \) = \) \( (500 \text{ kg}) v_{\text{cannon final}} - \) 100 kg \( \) ____ m/s \( \)

\( v_{\text{cannon final}} = \) \[ \) ____ \( (100 \text{ kg})(\) ____ m/s \( ) / ____ \text{ kg} = \) ____ m/s \( \)

SELF-EXPLANATION PROMPTS

1. What does “at rest” imply about the initial velocities of the cannon and the clown?

2. Is the initial condition (clown inside cannon) the same as if the two were sitting at rest next to one another? Explain.

Optional Practice Problems: 9.18, 9.19, 9.20, 9.42
Lesson 29: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

Two identical masses, \( M \), approach the origin with the same speed \( v \), at 45 degrees from the horizontal.

They collide and stick together. What are the speed and direction of motion after collision?

STRATEGY (Fill in the blanks.)

We apply the conservation of __________________ to determine the motion after collision.

The \( y \)-component of the momentum after collision must be zero because ______.

The \( x \)-component of the momentum before collision is ______

CALCULATION (Fill in the blanks.)

\[
2Mv_{\text{final}} = Mv \cos 45^\circ + \text{__________}
\]

\[
v_{\text{final}} = v \cos (45^\circ) \text{ in the positive } x\text{-direction.}
\]

SELF-EXPLANATION PROMPTS

1. Is this collision elastic?

If your answer is yes, explain your reasoning? If you answer is no, calculate the change in kinetic energy.

Optional Practice Problems: 9.43, 9.68, 9.77
Lesson 31

Rotational Motion

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- There is an optional *Equation Dictionary* entry in Appendix D for this lesson (1 PF pt).

Learning Objectives

[Obj 49] Explain the relation between the rotational motion concepts of angular displacement, angular velocity, and angular acceleration.

[Obj 50] Use equations of motion for constant angular acceleration to solve problems involving angular displacement, angular velocity, and angular acceleration.

[Obj 51] Use calculus to solve problems involving motion with non-constant angular acceleration.

Notes

Documentation Statement:
Worked Examples

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

The Smoky Hills Wind Farm near Salina, Kansas employ 140,000 pound Vestas V80 1.8-megawatt wind turbines. The three-blade turbines have a diameter of 80 m and operate at 15.5 to 16.8 rpm (revolutions per minute.)

a) What is the linear speed of the blade tip at maximum rotational speed?

b) What is the centripetal acceleration at the tip of the blade at the maximum speed?

c) If the blade slows down from maximum speed to rest in 30 seconds, through how many revolutions does it turn?

STRATEGY

We use the relation: linear quantity = (radius) times (corresponding angular quantity).

\[ s = r\theta \]
\[ v = r\omega \]
\[ a_t = r\alpha \]

The above relations are valid if the angles are measured in radians. The tangential acceleration \( a_t \) is non-zero if the angular speed is changing. Whenever the angular speed is non-zero, there is always a centripetal acceleration, \( \frac{v^2}{r} \), responsible for changing the direction of the tangential velocity.

IMPLEMENTATION

The angular speed is given in revolutions per minute. Since there are \( 2\pi \) radians in a revolution and 60 seconds in a minute, we multiply rpms by \( \frac{2\pi}{60} \) to get the angular speed in radians per second.

To obtain the tangential speed, we use \( v = r\omega \). The centripetal acceleration is then \( a_r = \frac{v^2}{r} \).

The kinematics equations for angular quantities mimic kinematics equations for linear motion. For constant angular acceleration \( \alpha \), the relation between \( \theta \), \( \omega \), \( \alpha \), and time is:

\[ \omega^2 = \omega_0^2 + 2\alpha(\theta_f - \theta_i) \]
CALCULATION

a) Maximum angular velocity:
\[ \omega_{\text{max}} = \frac{16.8 \times 2\pi}{60} = 1.76 \text{ rad/sec} \]

b) Maximum linear speed of the tip:
\[ v_{\text{max}} = r\omega = 40 \text{ m} \times 1.76 \text{ rad/sec} = 70.4 \text{ m/s} \]

c) Centripetal acceleration at the tip:
\[ a_r = \frac{v^2}{r} = \omega^2 r = 123.9 \text{ m/s}^2 \]

d) During the 30 seconds slow-down the blade undergoes an angular deceleration
\[ \alpha = \frac{\omega - 0}{t} = 0.06 \text{ rad/s}^2 \] and it turns through \[ \theta = \frac{\omega^2}{2\alpha} = 25.8 \text{ radians} = 4 \text{ revolutions} \]

Note: Compare \[ \omega^2 = \omega_0^2 + 2\alpha(\theta_f - \theta_i) \] for rotational motion to \[ v^2 = v_0^2 + 2a(x - x_0) \] for linear motion.

SELF-EXPLANATION PROMPTS

1. Show the conversion of 15.5 rpm to rad/s.

2. The angular measure radian is defined as the ratio of the arc length to the radius. Convert 1 degree to radians. Convert 1 radian to degrees.

3. If an object is rotating with a non-zero angular velocity \( \omega \) and zero angular acceleration \( \alpha \), is there a centripetal acceleration? If an object is rotating with a non-zero angular velocity \( \omega \) and non-zero angular acceleration \( \alpha \), what is the total linear acceleration?
Pre-Class Problem

STATEMENT OF THE PROBLEM

A 3-m diameter flywheel is spinning up with an angular acceleration of 3 rad/s². How long does it take the flywheel to reach 12 rpm (revolutions per minute) if it starts from rest?

Answer: 0.4 seconds
Preflight Questions

2. What topic from the reading would you like to discuss during class?

2. Which of the following is the closest to one radian?

   a) 30°
   b) 60°
   c) 90°
   d) 180°

3. Two ants crawl onto the surface of a compact disc. Ant A is farther from the center of the disc than Ant B. The compact disc begins to spin. Which of the following statements is true?

   a) Ant A experiences a greater tangential acceleration than Ant B.
   b) Ant A experiences a greater angular acceleration than Ant B.
   c) Neither statement is true.
   d) Both statements are true.

4. CRITICAL THINKING: What is the approximate angular speed of the earth revolving around the Sun, in rad/day? Explain the reasoning you used in determining your answer.
Homework Problems

10.19
Lesson 32

Rotational Inertia & Torque

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- There is a non-graded PHYSICS KNOWLEDGE ASSESSMENT TEST this lesson.

Learning Objectives

[Obj 52] Explain the concept of torque and how torques cause change in rotational motion.
[Obj 53] Given forces acting on a rigid object, determine the net torque vector on the object.
[Obj 54] Determine the rotational inertia for a system of discrete particles, rigid objects, or a combination of both.
[Obj 55] Compare and contrast the concepts of mass and rotational inertia.

Notes
Worked Examples

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

You have a flat tire on your car and, in order to change the tire, you need to remove the lug nuts that secure the wheel to the car. If the 30-cm long wrench you are using to remove the nuts is at a 55° angle to the horizontal and you apply a force of 120 N directly down on the end of the wrench, what is the magnitude of the torque you exert on the lug nut?

STRATEGY

For this problem, we are interested in the applied torque $\tau$. Torque is the rotational analog to force; it is the effectiveness of a force to cause an object to rotate about a pivot point. To solve for torque, we need to consider 1) the magnitude of the applied force $F$, 2) how far from the pivot point the force is applied $r$, and 3) the angle that the force is applied $\theta$.

IMPLEMENTATION

Let’s draw a diagram and label the applied force vector $\vec{F}$, the vector $\vec{r}$ that goes from the pivot point to the where the force is applied, and the angle $\theta$ between $\vec{r}$ and $\vec{F}$. Note that the angle $\theta$ is not 55°, but $(180° - 55°) = 125°$.

The relation between $\tau$, $r$, $F$, and $\theta$ is: $\tau = \vec{r} \times \vec{F} = rF \sin \theta$

CALCULATION

The magnitude of the torque exerted on the lug nuts is $\tau = rF \sin \theta = (0.30 \text{ m})(120 \text{ N}) \sin 125° = 29 \text{ N m}$.

The units of torque are newton-meters (N m).
SELF-EXPLANATION PROMPTS

1. In your own words, explain how torque differs from force.

2. Why did we use 125° for the angle of the applied force and not 55°?

3. Explain how the magnitude of the torque exerted on the lug nuts would change if the force was applied in the middle of the handle rather than the end.
Pre-Class Problem

STATEMENT OF THE PROBLEM

If you apply a 45-N force perpendicularly to a door at distances of 1 m, a) determine the magnitude of the torque, and b) the magnitude of the angular acceleration if the door's rotational inertia, \( I \), is 30 kg m\(^2\).

Answer: (a) 45 N m; (b) 1.5 rad/s\(^2\)

Try it! (1PF pt): Calculate the magnitude of the torque if the force was applied at an angle of 25° instead.
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. Rank order the magnitude of the torques from smallest to largest. Each rod is 50-cm long from the pivot (●).

```
Rank Order: Smallest (1) ____ (2) ____ (3) ____ (4) ____ (5) ____ Largest
```

3. In order to spin faster about a vertical axis, an ice skater needs to decrease her rotational inertia. She could achieve that by

   a) stretching her arms farther away from the vertical rotation axis.
   b) bringing her arms closer to her body.
   c) lowering her body by bending her knees and squatting down.
   d) bending forward at her waist so her body is L-shaped.
   e) Rotational inertia can only decrease if her mass decreases.

4. CRITICAL THINKING: A book can be rotated about many different axes. The moment of inertia of the book will depend upon the axis chosen. Rank the choices A to C above in order of increasing moments of inertia and explain your ranking.

Documentation Statement:
## Homework Problems

10.30
Lesson 33

Rotational Analog to Newton’s Second Law

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- There is an optional *Equation Dictionary* entry in Appendix D for this lesson (1 PF pt).

Learning Objectives

[Obj 55] Compare and contrast the concepts of mass and rotational inertia.

[Obj 56] Use Newton’s second law and its rotational analog to solve problems involving translational motion, rotational motion, or both.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM
A 50-kg block and a 100-kg weight are connected with a rope, passing over a pulley as shown. The 50-kg block is on a 30° ramp where friction is negligible. The pulley is a solid disc whose radius is 0.2 m and whose moment of inertia is 2 kg m². The rope does not stretch.

When released from rest, what is the acceleration of the system, including direction?

STRATEGY
First, we draw free-body diagrams and apply Newton’s Second Law for each of the two masses and Newton’s Law for rotational motion for the pulley. We then solve the system of three equations for the common acceleration. The system of equations has three unknowns, the acceleration and the two tensions. Since the inertia of the pulley is not negligible, the tension on the left side of the pulley is not the same as the tension on the right side of the pulley.

IMPLEMENTATION
The 50-kg block, m:
The net force on the block is: \( T_2 - mg \sin 30° = ma_x \).
The normal force \( n \) equals the component of the weight perpendicular to the ramp, \( W_{my} \).

The 100-kg block, M:
The net force on the block is: \( T_1 - mg = -ma_y \).
The lengths of the arrows do not indicate the magnitudes of the forces since we don’t know those until we make the calculations. Note the negative sign for the acceleration, to be consistent with the direction chosen for the 50-kg mass.

The pulley:
Newton’s Law for rotation states that \( l\alpha = \tau \). \( l \) is the moment of inertia, \( \alpha \) is the angular acceleration and \( \tau \) is the torques.

\[ m = 50 \text{ kg} \quad M = 100 \text{ kg} \]
\[ \alpha = 30° \quad r_p = 0.2 \text{ m} \]
\[ l = 2 \text{ kg m}^2 \quad \ddot{a} = ? \]
torque, defined as the applied force multiplied by the perpendicular distance to the axis of rotation from the application point of the force.

The net torque on the pulley is: \( \tau_{\text{net}} = T_1 r - T_2 r \)

The Newton’s Law equation for the pulley reads: \( T_1 r - T_2 r = l \alpha \)

**CALCULATION**

The three equations now read:

\[
\begin{align*}
T_2 - mg \sin 30^\circ &= ma \\
T_1 - Mg &= -Ma \\
T_1 r - T_2 r &= l \alpha
\end{align*}
\]

The angular acceleration and the linear acceleration are related by \( a = \alpha r \).

Solving for the acceleration we get:

\[
a = \frac{mg - Mg \sin 30^\circ}{m + M + \frac{l}{r^2}} = 2.2 \text{ m/s}^2
\]

The sign of the calculated acceleration is positive. That means that the 50-kg mass is accelerating up the ramp and the 100-kg weight is accelerating down.

**SELF-EXPLANATION PROMPTS**

1. **Justify** why each coordinate system on the free-body diagrams was used.

2. **Justify** the negative sign used for the acceleration in the equation of motion for the 100-kg weight.

3. **Explain** in your own words why the tensions on the two sides of the pulley are different.
Pre-Class Problem

STATEMENT OF THE PROBLEM

What magnitude of torque has to be applied to a 2.3-kg, 18-cm diameter, solid disk rotating at 800 rpm to stop it in 10 seconds?

Answer: 0.078 N m
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. Which statement is correct?
   a) If torque increases, rotational inertia must increase.
   b) The rotational inertia of an object does not depend on the location of its axis of rotation.
   c) An object with more mass has a higher rotational inertia than an object with less mass.
   d) Rotational inertia measures an object’s resistance to changes in its rotational motion.

3. Rank order the angular acceleration $\alpha$ of each case.
   The objects are connected with massless rods of lengths shown. The forces shown are the only forces acting on the objects causing rotation about the pivot point (●).

   a) $\alpha_B < \alpha_A < \alpha_D < \alpha_C$
   b) $\alpha_A < \alpha_D < \alpha_B < \alpha_C$
   c) $\alpha_D < \alpha_C < \alpha_A < \alpha_B$
   d) $\alpha_C < \alpha_D < \alpha_A < \alpha_B$

4. CRITICAL THINKING: The two blocks from the worked example problem, $m$ and $M$, are now hung directly down from the pulley as shown. Describe how the equation for the acceleration of the blocks would change for this scenario.
Homework Problems

10.56
MP
Lesson 34

Rotational Energy and Rolling Motion

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Learning Objectives

[Obj 57] Solve problems involving rotational kinetic energy and explain its relation to torque and work.
[Obj 58] Explain the relation between linear and angular speed in rolling motion.
[Obj 59] Use conservation of energy to solve problems involving rotating or rolling motion.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

A boulder on top of a hill breaks free and begins to roll down the hill without slipping. Approximating the boulder as a solid sphere with radius 3 m, what is the speed of the boulder at the bottom of the hill after it has undergone a vertical displacement of 100 m?

**STRATEGY**

We will use the principle of conservation of mechanical energy to solve for the speed of the boulder at the bottom of the hill.

\[
U_0 + K_0 = U_f + K_f
\]

Conservation of mechanical energy applies to this problem, because, although frictional force is acting on the boulder causing it to roll, no work is done by friction on the boulder.

**IMPLEMENTATION**

First, we need to determine the types of mechanical energy in both the initial (top of the hill) and the final (bottom of the hill) states. Since the boulder is initially at rest, it has only gravitational potential energy. The total mechanical energy \( E_0 \) at the top of the hill is given by

\[
E_0 = U_0 = mgh_0
\]

After the boulder has undergone a vertical displacement of 100 m, the gravitational potential energy has been converted to translational and rotational kinetic energy. In the final state, the boulder will have a combination of gravitational potential energy, translational kinetic energy and rotational kinetic energy. If we take the bottom of the hill to be where the gravitational potential energy is zero, the total mechanical energy \( E_f \) in the final state becomes

\[
E_f = K_{\text{trans}} + K_{\text{rot}} = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2
\]

The total mechanical energy at the top and at the bottom of the hill is the same (conserved), so our conservation of mechanical energy equation becomes

\[
mgh_0 = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2
\]

Now we can solve for the translational speed of the boulder at the bottom of the hill. The rotational kinetic energy is dependent on the rotational inertia and angular velocity of the boulder...
boulder. We are told that the boulder is (a) a solid sphere and (b) that is not slipping as it rolls – this means that we can use the rotational inertia of a solid sphere \( I = \frac{2}{5}mr^2 \) and the relationship between angular speed and translational speed \( \omega = \frac{v}{r} \) to put rotational kinetic energy in terms of the mass, radius, and translational speed of the boulder.

\[
mgh_0 = \left[ \frac{1}{2}mv^2 + \frac{1}{2}\left(\frac{2}{5}mr^2\right)\left(\frac{v}{r}\right)^2 \right] = \frac{7}{10}mv^2
\]

This equation can be simplified further as mass of the boulder appears on both sides of the equation and can be cancelled.

**CALCULATION**

Solving for the translational speed of the boulder at the bottom of the hill becomes:

\[
v = \sqrt{\frac{10gh_0}{7}} = \sqrt{\frac{10 \cdot 9.8 \text{ m/s}^2 \cdot 100 \text{ m}}{7}} = 37 \text{ m/s}
\]

Note: The speed of the boulder is independent of both the mass and the radius of the boulder.

**SELF-EXPLANATION PROMPTS**

1. Frictional force is needed for the boulder to roll, and not slide, down the hill. Explain why “no work is done by friction on the boulder”.

2. Explain why the boulder has only rotation and translation kinetic energy at the bottom of the hill.

3. How would the final speed change if the boulder was sliding down the hill instead of rolling? Derive an expression for the speed of the boulder at the bottom of the hill if it was sliding instead of rolling.
**Pre-Class Problem**

**STATEMENT OF THE PROBLEM**

In a pinball machine, a solid metal 0.050-kg ball is released from a spring and rolls around the machine hitting various targets. If the spring has a spring constant $k$ of 410 N/m and is compressed a distance $x$ of 22 cm, a) what is the rotational kinetic energy of the ball immediately after release? b) What is the translational kinetic energy of the ball immediately after release?

**Answer:** 0.047 J; 0.12 J

**Try it! (1PF pt):** Calculate the translation kinetic energy of the ball if it was sliding instead of rolling. Show you work.

**Answer:** 0.047 J; 0.12 J
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. A solid aluminum cylinder (mass $m$, radius $r$, rotational inertia $I = \frac{1}{2} MR^2$) and a solid steel cylinder (mass $2m$, radius $r$, rotational inertia $I = \frac{1}{2} MR^2$) start from the same position and roll down a ramp without sliding. At the bottom of the ramp,

   a) the aluminum cylinder has greater total kinetic energy.
   b) the steel cylinder has greater total kinetic energy.
   c) the cylinders have the same total kinetic energy.

3. A 4.5-kg bicycle tire ($I = 0.6$ kg m$^2$, $r = 37$ cm) is spinning on a mechanic’s stand at the same rate as if it were rolling at a linear speed $v_t = 10$ m/s. The mechanic applies the brake supplying a force to slow the rotation equivalent to $v_f = 5$ m/s rolling speed. What is the work done by the brake?

   a) $-16.4$ mJ
   b) $-164$ J
   c) $164$ J
   d) $16.4$ mJ

4. CRITICAL THINKING: An 8-kg wheel has a moment of inertia $I$ of 0.1 kgm$^2$. The wheel is rolling along without slipping. What is the ratio of its translational kinetic energy to its rotational kinetic energy? Explain how you obtained your answer.
Homework Problems

10.60
Lesson 35

Rotational Vectors and Angular Momentum

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Learning Objectives

[Obj 60] Determine the directions of the angular displacement, angular velocity and angular acceleration vectors for a rotating object.

[Obj 61] Determine the angular momentum vector for discrete particles and rotating rigid objects.

Notes
**Worked Example**

Study the given problem and solution, then answer the questions regarding the problem.

A car is driving clockwise around a circular race track. The tires on the car rotate 50 times every second. 

a) What is the car’s angular velocity as it travels due north and due east?  
b) What is the average angular acceleration of the car during the 10 seconds it takes to go from traveling due north to traveling due east.

**STRATEGY**

The problem asks about vector quantities, thus the answers have both a magnitude and a direction component which can be considered separately. First, we find the magnitude of the angular velocity and use this to find the magnitude of the average acceleration. To find the direction of the angular velocity and acceleration, we will use the right hand rule to find the velocity direction and from that, deduce the direction of the angular acceleration.

**IMPLEMENTATION**

To find the magnitude of the velocity, we apply unit analysis. We find the magnitude of the angular acceleration using the relation: \( \alpha = \frac{\Delta \omega}{\Delta t} \). To find the direction of the angular velocity, we apply the right hand rule.

**CALCULATION**

a) Angular velocity:  
\[
\omega = 50 \text{ rotations/second} \times 2\pi \frac{\text{radians}}{\text{rotation}} = 314 \frac{\text{radians}}{\text{s}} 
\]

b) Average angular acceleration:  
\[
\alpha = \frac{\omega}{t} = \frac{314 \text{ radians}}{10 \text{ s}} = 31.4 \frac{\text{rad}}{\text{s}^2} 
\]

c) The wheel is rotating forward, so if the fingers of our right hand point wrap forward and down – mimicking the motion of the wheel – then our thumb points to the left (west) which is the direction of the angular velocity. When the car is traveling east, the right-hand rule gives us a thumb pointing towards the top of the page (north). To find the direction of the acceleration vector, we draw a vector going from the tip of the west arrow to the tip of the north velocity vector. Thus the acceleration vector is to the north east.
SELF-EXPLANATION PROMPTS

1. Vectors can be added pictorially by drawing the vectors such that the tail of one vector connects to the tail of another vector. Explain how this approach is consistent with the above statement that the average acceleration vector goes from the tip of initial vector to the tip of the final vector.

2. Which direction is the velocity vector when the car is traveling west? South?

3. How would you describe the displacement vector of the car?
Pre-Class Problem

STATEMENT OF THE PROBLEM

A child is doing tricks with a remote-controlled airplane. Initially the propellers on the airplane are spinning at 1200 rpm as the plane dives straight toward the ground. Three seconds later, the airplane is in level-flight, flying north and the propellers are spinning at 1800 rpm. What was the average angular acceleration of the propellers?

Answer: \( \bar{\alpha} = 20.9 \frac{\text{rad}}{s^2} \),

34° above level flight
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. (True/False) The net torque \( \tau_{\text{net}} \) and angular acceleration \( \alpha \) always point in the same direction.
   
   a) True
   b) False

3. (True/False) The angular acceleration \( \alpha \) and angular velocity \( \omega \) always point in the same direction.
   
   a) True
   b) False

4. CRITICAL THINKING: How can a particle with linear velocity have angular momentum?

   Explain.
Homework Problems

11.16
Lesson 36

Conservation of Angular Momentum

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Learning Objectives

[Obj 62] Apply conservation of angular momentum to solve problems involving rotating systems changing rotational inertias and rotating systems involving totally inelastic collisions.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 2.0-kg projectile with a speed of 5.0 m/s strikes a fin on a wheel as shown the figure. The projectile strikes at a point 1.48 m to the right of the axis of rotation. After the projectile collides with the wheel it sticks to the fin at the point of impact. If the wheel has a rotational inertia of \( I = 100 \text{ kg m}^2 \), what will be the angular velocity of the wheel + projectile combination afterwards?

STRATEGY

This problem is an example of a rotational collision. If the wheel spins freely, there is no net torque acting on the system as a whole, so long as the system includes both the wheel and the projectile. In this case, the total angular momentum cannot change (see N2LRot).

IMPLEMENTATION

The initial angular momentum is that of the projectile:

\[
\vec{L}_i = \vec{r} \times \vec{p} = r_1 m v_0 \hat{k}
\]

The final angular momentum is that of the wheel plus the projectile attached to the fin:

\[
\vec{L}_f = (I + m r_1^2) \vec{\omega}_f
\]

Solving for the final angular velocity we get:

\[
\vec{\omega}_f = \frac{r_1 m v_0 \hat{k}}{I + m r_1^2}
\]

CALCULATION

\[
\vec{\omega}_f = \frac{(1.48 \text{ m})(2 \text{ kg})(5 \text{ m/s})}{100 \text{ kg m}^2 + (2 \text{ kg})(1.48 \text{ m})^2} = 0.14 \text{ rad/s}
\]

Notice that the result depends on the positioning of the launcher relative to the axle of the wheel.

Documentation Statement:
SELF-EXPLANATION PROMPTS

1. How does the result change if you move launcher so that the point of impact is at a greater distance from the axle of the wheel?

2. Can you tell if the collision is elastic or inelastic? Explain how you know, or why you cannot tell.

3. If you think it’s inelastic, how much energy is lost in the collision? If you think it’s elastic check to see if you’re correct.
Pre-Class Problem

STATEMENT OF THE PROBLEM

A 12-kg potter's wheel is spinning at 5.0 rpm and has a radius of 0.5 m. The potter throws a 2.0-kg block of clay onto the wheel with a velocity of 0.75 m/s in the same direction as the wheel. How fast is the wheel spinning immediately after the clay lands on the potter's wheel, in rpm?

Answer: 0.77rad/s or 7.33 rpm

Documentation Statement:
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. If a net torque is applied to a rigid object, which of the following is not true?

   a) The angular momentum of the object will change.
   b) The kinetic energy of the object will change.
   c) The object will experience an angular acceleration.
   d) The rotational inertia of the object will change.

3. An ice skater is spinning at 2 rad/sec with her arms outstretched. If she now pulls her arms in close to her body, her

   a) angular momentum remains the same.
   b) angular velocity increases.
   c) kinetic energy increases.
   d) All of the above are true.

4. CRITICAL THINKING: Explain why helicopters must have two rotors to function properly. Your explanation should involve angular momentum concepts.
Homework Problems

11.26
11.43
Lesson 37

Critical Thinking: Energy & Angular Momentum

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- There is an EXAM-PREP QUIZ this lesson.

Learning Objectives

[Obj 62] Apply conservation of angular momentum to solve problems involving rotating systems changing rotational inertias and rotating systems involving totally inelastic collisions.

Notes
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. A platform diver jumps off the diving tower and performs a twist maneuver. While in the air, he cannot change his
   a) rotational energy.
   b) rotational speed.
   c) rotational inertia.
   d) angular momentum.

3. What condition must be true in order for the angular momentum of an object to be conserved?
   a) No net external force acts on the object.
   b) No net external torque acts on the object.
   c) Both (a) and (b) are true.

4. CRITICAL THINKING: At the end of its life, a star goes supernova. Its core (radius = 20 Mm) collapses to form a neutron star (radius = 6.0 km). If the initial rotation rate of the star was 1 rev / 45 days, what is the rotation rate of the neutron star? (Treat the star as a solid sphere with \( I = \frac{2}{5}MR^2 \).)
Homework Problems

11.46
11.49
Lesson 38

Lab 6 – Conservation of Angular Momentum

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- There is a LAB this lesson.

Learning Objectives

[Obj 62] Apply conservation of angular momentum to solve problems involving rotating systems changing rotational inertias and rotating systems involving totally inelastic collisions.

Notes
Journal Questions

1. Briefly describe the purpose and goals of this lab. (One to two complete sentences)

Refer to Conceptual Example 11.1 in your textbook for the following questions.

2. When the boy jumps onto the merry-go-round,
   a) the total rotational inertia of the platform changes.
   b) the total angular momentum of the platform changes.
   c) Both (a) and (b) are correct.
   d) Neither (a) nor (b) is correct.

3. When the girl jumps onto the merry-go-round,
   a) the total rotational inertia of the platform changes.
   b) the total angular momentum of the platform changes.
   c) Both (a) and (b) are correct.
   d) Neither (a) nor (b) is correct.

4. In the example, the girl jumps in the same direction as the platform is rotating. Suppose, instead, that she jumps in the opposite direction, so that her velocity just before landing on the platform is counter to its rotation. Describe how you would mathematically account for this change when solving for the final angular speed of the merry-go-round.

5. Suppose the girl does not jump directly in the tangential direction, but at an angle θ to the tangential direction. Describe how you would mathematically account for this change when solving for the final angular speed of the merry-go-round.
Homework Problems

11.45
12.69
Lesson 39

*Simple Harmonic Motion*

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- There is an optional *Equation Dictionary* entry in *Appendix D* for this lesson (1 PF pt).

**Learning Objectives**

[Obj 63] Define simple harmonic motion and explain why it is so prevalent in the physical world.

[Obj 64] Determine the period and frequency of a simple harmonic oscillator from its physical parameters, and completely specify its equation of motion.

[Obj 65] Determine the velocity and acceleration of a simple harmonic oscillator from its equation of motion.

**Notes**
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

An ideal grandfather clock consists of a simple pendulum which swings back and forth once every second. What is a) the oscillation frequency, b) the angular frequency and c) how far from the end of the rod should the mass sit?

STRATEGY

First, connect the period to the frequency and angular frequency; then we can find the length of the pendulum associated with that angular frequency.

IMPLEMENTATION

1. In order to answer part (a) and (b), we need to consider how the frequency of simple harmonic motion relates to the period and also how the oscillation frequency of the pendulum depends on the angular frequency.

2. How does the length of the pendulum relate to the frequency of the pendulum?

CALCULATION

1. The period of the spring is inversely related to the oscillation frequency of the spring by $f = \frac{1}{T} = 1 \text{ Hz}$. The angular frequency is related to the oscillation frequency by $\omega = 2\pi f = 2\pi \text{ radians/s}$.

2. The angular frequency of the pendulum is given by $\omega = \sqrt{\frac{g}{L}}$. Therefore the pendulum is length is $L = 0.248 \text{ m}$.
SELF-EXPLANATION PROMPTS

1. In your own words, describe the difference between the oscillation frequency and the angular frequency.

2. In your own words, explain why the period of the pendulum is not dependent on the mass of the pendulum.

3. In your own words, describe why the period of the pendulum is inversely proportional to the length of the pendulum.
**Pre-Class Problem**

**STATEMENT OF THE PROBLEM**

A space probe is sent to a distant planet to determine if it is suitable for colonization. After having successfully met all the other criteria, there is one remaining test: is the gravitational pull of the planet within 30% of Earth’s normal gravity? The probe contains a simple pendulum which it uses to determine the gravitational constant of that planet. The compact pendulum is only 5.0 cm long and takes 0.33 seconds to move from the left most part of its swing to the center of its swing. Is the planet suitable for colonization?

![Diagram of a pendulum with 0.05 m and 0.33 s labels]

**Answer:** No, since $g_{new} = 1.14 \text{ m/s}^2$
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. Astronauts in space took a coiled spring of known spring constant $k$, attached a bob (small mass) to it, and set it oscillating. Measuring the period, they could determine
   a) the time of day the acceleration due to gravity
   b) the mass of the bob
   c) the weight of the bob

3. An adult and a child are sitting on adjacent identical swings. Once they get moving, the adult, by comparison to the child, will necessarily swing with
   a) a much greater period
   b) a much greater frequency
   c) the same period
   d) the same amplitude

4. CRITICAL THINKING: An oscillation is a physical phenomenon characterized by the fact that the configuration of the physical system repeats itself over and over again. Simple harmonic oscillations are a special case. An oscillation is simple harmonic if the period does not depend on the amplitude. In the following set, identify the oscillations that are simple harmonic, the ones that are approximately simple harmonic, and the ones that are not simple harmonic. Briefly explain your reasoning for each.
   a) The pendulum in a grandfather clock.
   b) A boat in water pushed down and released.
   c) A child on a swing.
   d) A mass hanging from an ideal spring.
   e) A ping pong bouncing on the floor.
Homework Problems

13.22
13.67
Lesson 40

Energy in Simple Harmonic Motion

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Learning Objectives

[Obj 66] Determine the potential and kinetic energies of a simple harmonic oscillator at any point in its motion, and describe the time dependence of these energies.

Notes
Worked Example

Study the given problem and solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A motionless mass is connected to a spring (with a spring constant of 85 N/m) which is compressed 30 cm from its equilibrium position. The mass, which is resting on a frictionless surface, is then released. At what position will the kinetic energy of the system be equal to exactly half the potential energy of the system?

STRATEGY

Since the spring starts at rest, the system has potential energy, but no kinetic energy. When the spring is released, the total mechanical energy of the system is conserved. This means that when the initial potential energy is equal to 2/3 of its initial value, the kinetic energy will be half the potential energy of the system.

IMPLEMENTATION

1. What is the spring potential energy of the system as a function of position?

2. What is the total mechanical energy of the system?

3. We then solve for the position where the potential energy is equal to 2/3 of its initial value.

CALCULATION

1. \( U_{spring\ potential} = \frac{1}{2} k \Delta x^2_{\ initial} = 3.83 \text{ J} \)

2. Since the system is initially at rest, the total mechanical energy is equal to the initial potential energy.

3. \( U_{x_2} = 2.55 J = \frac{1}{2} k \Delta x^2_{\ where \ K=1/2U} \). Solving for position gives \( \Delta x_{\ where \ K=1/2U} = 24.5 \text{ cm} \).
SELF-EXPLANATION PROMPTS

1. Why don’t you need to explicitly calculate the kinetic energy of the system?

2. What point is the final answer for displacement relative to?

3. Why does the point where the potential energy is equal to 2/3 its initial value correspond to the point where the kinetic energy is half the potential energy?
Pre-Class Problem

STATEMENT OF THE PROBLEM

A motionless mass is connected to a spring which is stretched 45 cm from its equilibrium position. The mass, which is resting on a frictionless surface, is then released. The maximum kinetic energy of the system is 10.6 J. What is the spring constant of the spring?

Answer: 132 N/m
Preflight Questions

1. What topic from the reading would you like to discuss during class?

2. For the simple harmonic motion of a mass on a spring without friction, it is true that
   a) the energy is independent of the amplitude
   b) the energy is independent of the period
   c) both (a) and (b)
   d) neither (a) nor (b)

3. The position $x(t)$ of a simple harmonic oscillator is shown to the right as a function of time. Which of the graph sets below correctly represent the kinetic and potential energies of the oscillator?

   a) Graph A is the potential energy, graph C is the kinetic energy.
   b) Graph C is the potential energy, graph A is the kinetic energy.
   c) Graph B is the potential energy, graph D is the kinetic energy.
   d) Graph D is the potential energy, graph B is the kinetic energy.

4. CRITICAL THINKING: For a given harmonic oscillator, if the spring constant and the mass are both doubled but the amplitude remains the same, explain what happens to the mechanical energy of the oscillator.
Homework Problems

13.29
13.63
Block 4 Review

Learning Objectives

[Obj 49] Explain the relation between the rotational motion concepts of angular displacement, angular velocity, and angular acceleration.

[Obj 50] Use equations of motion for constant angular acceleration to solve problems involving angular displacement, angular velocity, and angular acceleration.

[Obj 51] Use calculus to solve problems involving motion with non-constant angular acceleration.

[Obj 52] Explain the concept of torque and how torques cause change in rotational motion.

[Obj 53] Given forces acting on a rigid object, determine the net torque vector on the object.

[Obj 54] Determine the rotational inertia for a system of discrete particles, rigid objects, or a combination of both.

[Obj 55] Compare and contrast the concepts of mass and rotational inertia.

[Obj 56] Use Newton's second law and its rotational analog to solve problems involving translational motion, rotational motion, or both.

[Obj 57] Solve problems involving rotational kinetic energy and explain its relation to torque and work.

[Obj 58] Explain the relation between linear and angular speed in rolling motion.

[Obj 59] Use conservation of energy to solve problems involving rotating or rolling motion.

[Obj 60] Determine the directions of the angular displacement, angular velocity and angular acceleration vectors for a rotating object.

[Obj 61] Determine the angular momentum vector for discrete particles and rotating rigid objects.

[Obj 62] Apply conservation of angular momentum to solve problems involving rotating systems changing rotational inertias and rotating systems involving totally inelastic collisions.

[Obj 63] Define simple harmonic motion and explain why it is so prevalent in the physical world.

[Obj 64] Determine the period and frequency of a simple harmonic oscillator from its physical parameters, and completely specify its equation of motion.

[Obj 65] Determine the velocity and acceleration of a simple harmonic oscillator from its equation of motion.

[Obj 66] Determine the potential and kinetic energies of a simple harmonic oscillator at any point in its motion, and describe the time dependence of these energies.

Notes
Lesson 31: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 3-m diameter flywheel is spinning up with an angular acceleration of 3 rad/s^2. What is the total linear acceleration at the rim of the wheel at the instant when its angular velocity is 12 rpm?

STRATEGY (Fill in the blank)

Since the wheel has an angular acceleration, there is tangential linear acceleration \( \vec{a}_t \) where \( \vec{a}_t = \omega \alpha \). We note that the linear acceleration depends on the radius, i.e. points farther from the center have larger linear accelerations (as well as larger linear velocities.) The rotating points also have a centripetal acceleration, directed at the center of rotation. We calculate both accelerations and add the two vectors, which are perpendicular to each other.

CALCULATION

The tangential acceleration \( a_t = \omega \alpha \times \omega = 4.5 \text{ m/s}^2 \)

The centripetal acceleration is equal to \( \omega^2 r \). In terms of angular velocity \( a_c = \omega^2 r \).

For the equation \( a_c = \omega^2 r \) to be valid, the angular velocity has to be in radians.

To convert 120 rpm into radians we write \( \omega = 12 \frac{\text{rev}}{\text{min}} \times \frac{\text{rad}}{\text{rev}} \times \frac{\text{min}}{60 \text{ sec}} = 1.3 \text{ rad/s} \).

The centripetal acceleration is then \( \omega^2 r = 2.5 \text{ m/s}^2 \).

The magnitude of the total acceleration is 5.1 m/s^2.

The direction of the total acceleration is 60.9 degrees.

SELF-EXPLANATION PROMPTS

1. Explain in your own words why the angular speed of a rigid rotating object is the same for all parts of the object while the linear speeds of different parts of the object vary with the radius.

2. Justify the relation \( a_c = \omega^2 r \).

3. Is the centripetal acceleration in any way related to the angular acceleration?

Optional Practice Problems: 10.13, 10.18, 10.41
Lesson 32: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

Two weights of masses 2m and m are attached to either end of a thin rod of length L. Calculate the rotational inertia of the mass-rod system about a perpendicular rotational axis through the center of the rod. Assume the thin rod has negligible mass.

STRATEGY (Fill in the blanks.)

The rotational inertia of an object that consists of multiple discrete masses depends on how those discrete masses are spatially distributed relative to the axis of rotation.

For this problem, the object consists of three components: ______________, ______________, and __________ connecting the two weights. The thin rod has negligible mass, so it does not contribute to the rotational inertia of the system. To determine the rotational inertia of the system, we will sum the rotational inertia of each component.

CALCULATION (Fill in the blanks.)

The rotational inertia of the object is determined by summing the individual rotational inertias for each discrete mass.

When the rotation axis is through the center of the rod, the rotational inertia is:

\[ I = \sum m_i r_i^2 = \text{___________} + \text{___________} = \frac{3}{4} m l^2 \]

SELF-EXPLANATION PROMPTS

1. In your own words, explain rotational inertia of an object.

2. In this problem, why was the distance from the rotation axis \( r \) equal to \( L/2 \) for both weights?

3. Would the rotational inertia of the object increase, decrease, or stay the same if the rotation axis was at one end instead of through the center of the rod?

Optional Practice Problems: 10.22, 10.24, 10.29
Lesson 33: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 50-kg bucket is hanging from a rope, which is wound around a 20-kg solid disc. The diameter of the disk is 50 cm. The mass of the rope is negligible compared to the other masses in the problem. What is the acceleration of the falling bucket?

STRATEGY (Fill in the blanks.)

We will draw free-body diagrams for the two objects of interest: the bucket and disk. We will then apply Newton’s Second Law to each object and the system of two equations for the unknown acceleration.

CALCULATION (Fill in the blanks.)

Newton’s Law for the falling bucket:

\[ \sum F_y = ma_y \]

\[ \hphantom{=} +m = ma \]

Newton’s Law for the rotating disc:

\[ \sum \tau = I \alpha \]

\[ \hphantom{=} +l = I \alpha \quad I = \frac{1}{2} M_{\text{disc}} R^2 \quad a = \alpha R \]

Eliminating \( T \) from the two equations and solving for the acceleration we get

\[ a = \frac{mg}{\frac{1}{2} M_{\text{disc}} + m} = 8.2 \text{ m/s}^2 \]

SELF-EXPLANATION PROMPTS

1. Supply the missing algebra. Write down the two equations of motion, eliminate the tension and solve for the acceleration.

2. In a few sentences try to explain why the radius of the disc does not affect the final result.

Optional Practice Problems: 10.32, 10.59
Lesson 34: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

You are helping to unload cargo off a C-130 Hercules aircraft. The cargo is packed in barrels, so you decide it will be easier to roll the barrels down the ramp at the back of the aircraft and off the plane. If a barrel has a speed of 0.5 m/s when it reaches the ramp, what is its speed after it has rolled down the ramp without slipping and off the plane? The vertical height of the ramp is 1.5 meters.

STRATEGY (Fill in the blanks.)

We will use the principle of conservation of _____________ to solve for the speed of the barrel at the end of the ramp.

CALCULATION (Fill in the blanks.)

Starting with conservation of ____________,

\[ U_0 + (K_{\text{rot}} + K_{\text{trans}})_0 = (K_{\text{rot}} + K_{\text{trans}})_f \]

we substitute in the types of energy in the initial (at the top of the ramp) and final (at the bottom of the ramp) states.

\[ \text{______ + (______ + ______)}_0 = (\frac{1}{2}mv^2 + \frac{1}{2}I\omega^2)_f \]

Now, we replace \( \omega \) with \( \omega = \frac{v}{r} \) because the barrel is not __________ and put rotational inertia in terms of mass and radius of the barrel.

(Approximating the barrel as a solid cylinder, its rotational inertia is \( I = \frac{1}{2}MR^2 \))

\[ mgh + \frac{1}{2}mv_0^2 + (______)v_0^2 = \frac{1}{2}mv^2 + \frac{1}{2}(______)v^2 \]

Solving for the final speed of the barrel at the end of the ramp gives:

\[ v = \sqrt{\text{___________}} = 4.5 \text{ m/s} \]

SELF-EXPLANATION PROMPTS

1. Compare the rotational inertia of a hollow cylinder to a solid cylinder. If the barrel were instead hollow, would it reach the bottom of the ramp earlier or later than if it was solid? Assume the same initial speed.

2. Does the final answer depend on the mass or the radius of the barrel? Explain.

Optional Practice Problems: 10.38, 10.36, 10.61
Lesson 35: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

What is the magnitude and direction of the angular momentum of a 10-kg solid disc, 60 cm in diameter, rotating counter-clockwise at 120 rpm around its central axis?

STRATEGY (Fill in the blanks.)

We will use the relation, \( \vec{L} = \vec{\omega} \times \vec{r} \), and the \___________ \ rule to find the answer.

CALCULATION (Fill in the blanks.)

First, we need to convert rotational speed from rpm to rad/s

\[
\omega = \frac{\text{rad}}{s}
\]

For a solid disc rotating around its central axis

\[
I = \text{mass} \times \text{radius}^2 = 0.45 \text{kgm}^2
\]

Now substitute to get:

\[
L = \text{moment of inertia} \times \text{angular velocity} = 5.66 \text{kgm}^2\text{s}^{-2}
\]

The direction, from the right-hand rule, is \___________.

SELF-EXPLANATION PROMPTS

1. How would the answer change if the disc was a hoop?

2. Why are there no units of radians in the final answer?

Optional Practice Problems: 11.15, 11.19, 11.22
Lesson 36: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

Two disks are rotating at different speeds along the same axis as shown. The top disk is 5 kg and rotating at 1.0 rad/s; the bottom disk is 10 kg and rotating at 2.0 rad/s. If the top disk is released and lands on the bottom disk, what is the final angular speed of the combined disks?

STRATEGY (Fill in the blanks.)

This problem is an example of a _________________. There is no net torque acting on the system, so the total angular momentum does not change (conserved).

CALCULATION (Fill in the blanks.)

The initial angular momentum of the top disk is:

\[ \vec{L}_i = I\vec{\omega} = \text{__________} \]

The initial angular momentum of the bottom disk is:

\[ \vec{L}_i = I\vec{\omega} = \text{__________} \]

The final angular momentum of the combined disks can be determined by _________________.

\[ \vec{L}_i = \vec{L}_f \]

Solving for the final angular velocity, we get:

\[ \vec{\omega}_f = \text{__________}; \text{(direction - __________)} \]

SELF-EXPLANATION PROMPTS

1. Show that kinetic energy is not conserved in the example.

2. Example why angular momentum is conserved but kinetic energy is not.

Optional Practice Problems: 11.25, 11.28

Documentation Statement:
Lesson 39: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A young girl decides to build a simple pendulum to knock over a toy car. To do so, she ties one end of a 40-cm string to the railing and a rubber ball to the other end of the string. The setup is designed so that the ball will hit the toy car when the pendulum is at the lowest point of its arc. The girl positions the pendulum so that the string is tight and the ball is 10 cm off the ground. How long does it take for the ball strike the toy car?

STRATEGY (Fill in the blanks.)

First, we find the period of the pendulum. The time it takes the ball to swing from its initial position to the collision point is ¼ the period.

CALCULATION (Fill in the blanks.)

The time it takes the pendulum to strike the car is \( \frac{1}{4} \) = 0.32 s.

SELF-EXPLANATION PROMPTS

1. Why is the final answer only ¼ of the period?

2. Why doesn’t the initial height of the pendulum affect the period of the swing?

Optional Practice Problems: 13.31, 13.22, 13.25
Lesson 40: “Are you ready?”

Read the problem below and work through the guided solution, then answer the questions regarding the problem.

STATEMENT OF THE PROBLEM

A 2.0-kg mass is attached to a vertically oriented spring which has a spring constant of 25 N/m. The spring is compressed 31 cm relative to its equilibrium point. What is the speed of the mass at the equilibrium point of the spring?

STRATEGY (Fill in the blanks.)

This is a conservation of energy problem. The mass initially has both gravitation potential energy and spring potential energy. At the equilibrium point, all of this energy is converted to kinetic energy.

CALCULATION (Fill in the blanks.)

For convenience, we choose the equilibrium point of the spring to be the reference point.

The gravitational potential energy is \( P_{\text{gravitation}} = \ldots = 6.99 \text{ J} \)

The spring potential energy is \( P_{\text{spring}} = \ldots = 2.40 \text{ J} \)

At the equilibrium point, \( K = \ldots = \frac{1}{2}mv^2 \).

Solving for velocity we find that \( v = 3.1 \text{ m/s} \).

SELF-EXPLANATION PROMPTS

1. Why is the equilibrium point a convenient choice of origin?

2. Explain, in your own words, how you found the kinetic energy at the equilibrium point.

3. Why can the spring energy be combined with the gravitational energy?

Optional Practice Problems: 13.41, 13.43, 13.77
Appendix A: Lab Report Template

Purpose

A formal lab report is essential to the scientific process. It is the most common way that the results of a scientific study are communicated to the scientific community. You may assume your audience is scientifically literate but has not performed the experiment in question.

Format

Use the following guidance to format your report:

- Use a clearly readable 12-point font
- Set the page borders to 1”
- Space lines within the same paragraph at 1.0 or 1.15
- Separate paragraphs with a double space
- Use section headings to identify transitions between sections
- Refer to your experiment and/or calculations in the past tense
- Use the third-person (i.e., avoid using “I” or “we”)
- Use scientific notation where appropriate and include all units (e.g., $1.1 \times 10^6$ m)
- Cite any outside sources (other than your textbook) using MLA format
- If you include a figure, center it in the page and ensure it has a descriptive caption underneath it. You may neatly hand-draw figures.
- Graphs or plots may be used to summarize data and show analysis. They must include a title and labeled axes and must not be done by hand. Ensure the graph or plot is large enough to be clearly read and interpreted by your reader. For clarity, you may choose to cross-reference the graph or plot and include it as an attachment at the end of your report.
- Your instructor may provide additional guidance.

Sections

Use the following format to create your lab report. Remember there is a balance between too little information and too much information. You want your report to include what is relevant without becoming too long, complicated, or confusing. Your reader will likely not struggle through a poorly written document, which means he or she will never learn of your results or findings.

Title Page

Use a separate title page. Ensure the title of your report is centered near the top of the first page. List all contributors to the lab report underneath the title. Also include the course name and number and the date. At the bottom of the title page, neatly include your documentation statement for any outside help you obtained (but not outside references).


**Introduction**

In this section, you will provide a brief introduction to your reader about your purpose and the importance of your work. You should also briefly summarize any pertinent material, including relevant equations or concepts.

**Experimental Methods**

In this section, you must succinctly describe the methods you used to obtain your data. In general, readers will be most interested in reading about your data, results, and conclusions, but if your results are interesting, a reader will also be interested in how you obtained your data. Focus on keeping this section complete but concise. Graphics and figures should be used sparingly in this section.

**Results and Discussion**

This is an extremely important section of your report. Here you should communicate what you found and draw pertinent conclusions based on interpretation of your data. Graphics, figures and Excel plots may be used to effectively communicate your results. Follow the guidance in the Format section. Make sure your results are corroborated or justified by the data you obtained. Keep in mind that not all data is numerical. For the labs in this course, you may be able to make some powerful conclusions based on qualitative observations.

**Conclusion**

Here you will summarize your results. Ensure you do not introduce any new information in this section.

**References**

If you cited any references, include them here using MLA format.

**Appendixes (if needed)**

Use this section to place any large or complicated graphs or data plots.

**Grading**

See the individual lab lessons for the rubric your instructor will use to grade your report. You will be graded on the appearance and quality of your lab report.
Appendix B: Significant Figures, Uncertainty and Error Propagation

References:


Numeric calculations and experimental measurements are only as accurate (or reliable) as the least precise measurement. Every physical measurement has uncertainty and laboratory measurements do not yield exact results. Errors and uncertainties in physical experiments must be reduced through experimental techniques and repeated measurements – remaining uncertainty must be estimated and reported to establish the validity of the result.

The term error is defined as the difference between observed (or calculated) value and the “true” value. In laboratory measurements we rarely know the true value, therefore we must establish systematic means of determining the validity of our experimental results. Errors that originate from mistakes in measurement are known as illegitimate (gross) errors, and are corrected through attention and careful repeated measurements. In our experiments we are concerned with uncertainties introduced by random fluctuations in measurements and systematic errors that limit the precision and accuracy of our results. Random errors are fluctuations that occur in observations each time a measurement is repeated. Random error may be reduced through laboratory technique or repeated observations. Systemic errors are difficult to detect and may make all our results vary with reproducible discrepancy. Systemic error may result from poorly calibrated equipment or bias by the observer.

Accuracy is a measure of how close the result is to the true value. Precision is a measure of how well the result has been determined (without regard to agreement with true value). Precision is also a measure of an experiment’s reproducibility. Figure B1 illustrates the difference between accuracy and precision.

FIG. B1. Accuracy and precision demonstrated through target practice. Target (a) is accurate, but not precise, while (b) is precise but not particularly accurate.
**Significant Figures**

The number of digits in reporting an experimental result implies the precision of a measurement and uncertainty should be reported specifically with each numeric result.

**Rules for number of significant figures:**

1. Leftmost nonzero digit is the most significant digit.
2. If there is no decimal point, the rightmost nonzero digit is the least significant digit.
3. If there is a decimal point, the rightmost digit is the least significant digit, even if it is a zero.
4. The number of digits between the most and least significant digit count are known as the as significant figures.

**Rules for significant figures in calculating numbers:**

1. Multiplication/division. The numeric result cannot have more significant figures than any of the original numbers.
2. Addition/subtraction. The result cannot have more significant digits to the right of the decimal point than any of the original numbers.
3. Rounding results. Insignificant digits are dropped from the result and the last digit is rounded for best accuracy.

**Uncertainty**

Every physical measurement has uncertainty due to the accuracy or precision of laboratory equipment and the random distribution of our data. Since we do not normally know the actual error (discrepancy from the true value) in experimental results, we seek to develop a method of determining the estimated error. Analysis of the distribution of repeated measurements can lead to an understanding of the experimental error, reported as the spread of the distribution. Determine the best value $x_{\text{best}}$ and uncertainty estimate $\delta x$, and report the result as

$$ x_{\text{best}} \pm \delta x. \quad (B1) $$

Uncertainty in experimental measurements can be estimated in a number of ways, including standard reading of analog or digital instruments, or statistical analysis of the distribution of repeated measurements.
Uncertainty in Analog Measurements

Uncertainty in reading analog devices (rulers, balances, graduated cylinders, etc.) is estimated as one half the smallest division marked on the device.

Example: A length measurement is taken using a ruler marked in increments of 1 mm as shown in Figure B2. Uncertainty is one half the smallest increment, or 0.5 mm. The length is reported as 26 ± 0.5 mm according to Eqn. B1.

Uncertainty in Digital Measurements

Many modern laboratory devices are digital (scales, timers, multimeters, etc.). Systematic error is reduced if the device is properly calibrated. Estimated uncertainty is the least significant digit that can be displayed if the reading is constant (i.e. not fluctuating). If the reading is fluctuating, repeated measurements must be taken and other methods of estimating uncertainty must be used.

Example: A time measurement is taken using a photogate timer reading to one-thousandth of a second as shown in Figure B3. Uncertainty is the least significant digit, or 0.001 s. The time measurement is recorded as 1.673 ± 0.001 s according to Eqn. B1.

Uncertainty in Repeated Measurements

Repeated measurements help us extract the best value of our experimental results and determine the estimated error with confidence. As we take more measurements, we expect a pattern to emerge with data points distributed around the correct value (assuming we correct for systematic errors).

Suppose during an experiment, we take a sample of \( N \) measurements of a quantity \( x \).

The arithmetic mean \( \bar{x} \) of the experimental distribution is given as

\[
\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i .
\] (B2)

The expression for the standard deviation \( \sigma \) of the sample population is given by

\[
\sigma = \sqrt{\frac{1}{(N-1)} \sum_{i=1}^{N} (x_i - \bar{x})^2}
\] (B3)

which represents the best estimate for the deviation squared of the parent distribution (as if we took and infinite number of measurements) based on the smaller sample distribution. The standard deviation \( \sigma \) represents a quantitative measure of the uncertainty in any single measurement. If we
were to take another sample measurement there is a 68.2% chance it will be within $\bar{x} \pm \sigma$, a 95.4% chance it will be within $\bar{x} \pm 2\sigma$, and a 99.7% chance it will be within $\bar{x} \pm 3\sigma$, as shown in Figure B4.

Given repeated trials and calculations of the mean, it is possible to determine variation in the value of the mean. When determining experimental results with a large sample size, we seek a quantitative measure of the standard deviation of the mean, or the standard deviation in the sample mean relative to the true (mean) value.

$\sigma_{mean} = \frac{\sigma}{\sqrt{N}} = \sqrt{\frac{1}{N(N-1)} \sum_{i=1}^{N} (x_i - \bar{x})^2}$  
(B4)

Experimental results based on this sample distribution are reported as

$(\text{experimental value}) = \bar{x} \pm \sigma_{mean}$.  
(B5)

For small sample sets (three or fewer trials), we may estimate uncertainty using the expression

$\delta x = \frac{x_{max} - x_{min}}{2}$.  
(B6)

**Error Propagation**

Experimental quantities derived from measured values with uncertainty will in turn have uncertainty. Estimated uncertainty is calculated based on the mathematical operations used in the derivation. Suppose we measure values $(a, b, c, x, y, z)$ with uncertainty $(\delta a, \delta b, \delta c, \delta x, \delta y, \delta z)$. We seek the uncertainty in a calculated value $Q$.

**Addition or Subtraction with Uncertainty**

If

$$Q = a + b + c - x - y - z$$

then

$$\delta Q = \sqrt{(\delta a)^2 + (\delta b)^2 + (\delta c)^2 + (\delta x)^2 + (\delta y)^2 + (\delta z)^2}.$$  
(B7)

**Multiplication or Division with Uncertainty**

If

$$Q = \frac{abc}{xyz}$$

FIG. B4. Normal (Gaussian) distribution with standard deviation $\sigma$.  

xxiv
then
\[ \frac{\delta Q}{|Q|} = \sqrt{\left(\frac{\delta a}{a}\right)^2 + \left(\frac{\delta b}{b}\right)^2 + \left(\frac{\delta c}{c}\right)^2 + \left(\frac{\delta x}{x}\right)^2 + \left(\frac{\delta y}{y}\right)^2 + \left(\frac{\delta z}{z}\right)^2}. \] (B8)

**Multiplication by a Known Value with Uncertainty**

If \( Q \) is calculated by multiplying by a known value \( A \) (e.g. \( A = 2\pi \) or \( A = \frac{1}{2} \)) by a quantity \( x \) with uncertainty,

\[ Q = Ax \]

then
\[ \delta Q = |A| \delta x \] (B9)
or equivalently
\[ \frac{\delta Q}{|Q|} = \frac{\delta x}{|x|}. \] (B10)

**Uncertainty with Exponents**

If \( n \) is an exact number and

\[ Q = x^n \]

then
\[ \frac{\delta Q}{|Q|} = |n| \frac{\delta x}{|x|}. \] (B11)

**Reporting Experimental Values**

It should be emphasized that uncertainty estimates are only estimates and values should be presented with appropriate precision.

Rules for *reporting experimental values*:

1. The least significant figure in any reported value should be the same order of magnitude (same decimal position) as the uncertainty.
2. Estimated uncertainty is normally rounded to one significant figure.
Appendix C: Mathematics Reference

Quadratic Formula

Solutions of the quadratic equation \( ax^2 + bx + c = 0 \) are given by the quadratic formula.

\[
\text{Quadratic Formula} \quad x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}
\]

Coordinate Systems

Convention dictates right-handed coordinate systems. Alternate coordinate systems may be used – be sure to clearly indicate chosen coordinate axes. Two common coordinate systems used in physics are shown below.

**Cartesian Coordinate System**

\( \vec{r} = x \hat{i} + y \hat{j} + z \hat{k} \)

\( d\vec{r} = dx \hat{i} + dy \hat{j} + dz \hat{k} \)

**Spherical Coordinate System**

\( r \geq 0 \)
\( 0 \leq \theta \leq \pi \)
\( 0 \leq \phi \leq 2\pi \)

\( \vec{r} = r \sin \theta \cos \phi \hat{i} + r \sin \theta \sin \phi \hat{j} + r \cos \theta \hat{k} \)

\( d\vec{s} = dr \hat{r} + r d\theta \hat{\theta} + r \sin \theta d\phi \hat{\phi} \)

\( d\vec{a} = r^2 \sin \theta d\theta \, d\phi \, \hat{\phi} \)

\( dV = r^2 \sin \theta \, dr \, d\theta \, d\phi \)
**Trigonometry**

![Diagram of a right triangle with labels for hypotenuse, opposite, and adjacent sides]

\[
\begin{align*}
\sin \theta &= \frac{\text{Opp}}{\text{Hyp}} \\
\csc \theta &= \frac{1}{\sin \theta} = \frac{\text{Hyp}}{\text{Opp}} \\
\cos \theta &= \frac{\text{Adj}}{\text{Hyp}} \\
\sec \theta &= \frac{1}{\cos \theta} = \frac{\text{Hyp}}{\text{Adj}} \\
\tan \theta &= \frac{\sin \theta}{\cos \theta} = \frac{\text{Opp}}{\text{Adj}} \\
\cot \theta &= \frac{1}{\tan \theta} = \frac{\cos \theta}{\sin \theta} = \frac{\text{Adj}}{\text{Opp}}
\end{align*}
\]

---

**Law of Sines**

\[
\frac{\sin \alpha}{A} = \frac{\sin \beta}{B} = \frac{\sin \gamma}{C}
\]

**Law of Cosines**

\[C^2 = A^2 + B^2 - 2AB \cos \gamma\]

---

**Trigonometric Identities**

\[
\begin{align*}
\sin(-\theta) &= -\sin \theta \\
\cos(-\theta) &= \cos \theta \\
\sin^2 \theta + \cos^2 \theta &= 1 \\
1 + \tan^2 \theta &= \sec^2 \theta \\
1 + \cot^2 \theta &= \csc^2 \theta \\
\sin 2\theta &= 2 \sin \theta \cos \theta \\
\cos 2\theta &= \cos^2 \theta - \sin^2 \theta = 1 - 2\sin^2 \theta = 2\cos^2 \theta - 1 \\
\sin(\alpha \pm \beta) &= \sin \alpha \cos \beta \pm \cos \alpha \sin \beta \\
\cos(\alpha \pm \beta) &= \cos \alpha \cos \beta \mp \sin \alpha \sin \beta \\
\sin \alpha \sin \beta &= 2 \sin \left[\frac{1}{2}(\alpha \pm \beta)\right] \cos \left[\frac{1}{2}(\alpha \mp \beta)\right] \\
\cos \alpha + \cos \beta &= 2 \cos \left[\frac{1}{2}(\alpha + \beta)\right] \cos \left[\frac{1}{2}(\alpha - \beta)\right] \\
\cos \alpha - \cos \beta &= 2 \sin \left[\frac{1}{2}(\alpha + \beta)\right] \sin \left[\frac{1}{2}(\alpha - \beta)\right]
\end{align*}
\]
Vectors

Given vectors $\vec{A} = A_x \hat{i} + A_y \hat{j} + A_z \hat{k}$ and $\vec{B} = B_x \hat{i} + B_y \hat{j} + B_z \hat{k}$, 

$$\vec{A} \cdot \vec{B} = AB \cos \theta \quad \vec{A} \cdot \vec{B} = A_x B_x + A_y B_y + A_z B_z$$

$$|\vec{A} \times \vec{B}| = AB \sin \theta \quad \vec{A} \times \vec{B} = (A_y B_z - A_z B_y)\hat{i} + (A_z B_x - A_x B_z)\hat{j} + (A_x B_y - A_y B_x)\hat{k}$$

Exponentials and Logarithms

$$a^x a^y = a^{x+y} \quad e^{\ln x} = x \quad \ln(xy) = \ln x + \ln y$$

$$(a^x)^y = a^{x y} \quad \ln e^x = x \quad \ln \left(\frac{x}{y}\right) = \ln x - \ln y$$

$$a^x = e^{x \ln a} \quad \ln x^y = y \ln x \quad \log_n x = \frac{\ln x}{\ln 10}$$

$$e \approx 2.71828 \ldots \quad \ln(1) \equiv 0 \quad e^0 = 1$$

Derivatives and Integrals

$$\frac{d}{dx} \left[ f(x)g(x) \right] = g \frac{df}{dx} + f \frac{dg}{dx}$$

$$\frac{d}{dx} \left[ \frac{f(x)}{g(x)} \right] = \frac{1}{g^2} \left( g \frac{df}{dx} - f \frac{dg}{dx} \right)$$

$$\frac{d}{dx} x^n = nx^{n-1}, \quad \text{where } n \text{ is a constant.}$$

$$\frac{d}{dx} \sin ax = a \cos ax$$

$$\frac{d}{dx} \cos ax = -a \sin ax$$

$$\frac{d}{dx} e^{ax} = ae^{ax}$$

$$\frac{d}{dx} \ln ax = \frac{1}{x}$$

$$\frac{d}{dx} \frac{df(u)}{du} \frac{du(x)}{dx} = \frac{df(u)}{du} \frac{du(x)}{dx}$$

$$\int a \, dx = ax + C$$

$$\int ax^n \, dx = \frac{a}{n+1} x^{n+1} + C, \quad n \neq -1.$$
Taylor Series Expansions and Approximations

A Taylor series expansion of a real function $f(x)$ about a point $x = a$ is given by

$$f(x) = f(a) + f'(a)(x - a) + \frac{f''(a)}{2!}(x - a)^2 + \cdots = \sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!}(x - a)^n.$$

Series Expansions of Common Functions (for $|x| < 1$)

| For $|x| < 1$ |
|----------------|
| $e^x \approx 1 + x$ |
| $\sin x \approx x$ |
| $\cos x \approx 1 - \frac{x^2}{2}$ |
| $\ln(1 \pm x) \approx \pm x$ |
| $(1 + x)^p \approx 1 + px$ |
Appendix D: Equation Dictionary

On certain lessons, you will have the option to complete a worksheet on a particular equation for pre-flight points. The equation dictionary is designed: (1) to allow you to become more familiar with an equation, and (2) to enable you to create a highly organized and easily accessible study guide for exam preparation. The more time you spend creating meaningful entries to your equation dictionary, the more prepared you will be for exams in the course.

In the white box on the upper left corner, you will find the equation reference number. In the black box in the upper right corner, you will find the lesson number where the equation is first introduced. An example of a high-quality equation dictionary entry is shown below.
<table>
<thead>
<tr>
<th>Physics Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variables (include all units)</td>
</tr>
<tr>
<td>Description and Notes</td>
</tr>
<tr>
<td>Diagram</td>
</tr>
</tbody>
</table>

\[ \dot{v} = \dot{v}_0 + \dot{a}t \]
### Physics Concept

#### Variables (include all units)

#### Description and Notes

#### Diagram
### Physics Concept

### Variables (include all units)

### Description and Notes

### Diagram
<table>
<thead>
<tr>
<th>Variables (include all units)</th>
</tr>
</thead>
</table>

\[ W = \int \mathbf{F} \cdot d\mathbf{r} \]

**Physics Concept**

**Description and Notes**

**Diagram**
<table>
<thead>
<tr>
<th>Physics Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variables (include all units)</td>
</tr>
<tr>
<td>Description and Notes</td>
</tr>
<tr>
<td>Diagram</td>
</tr>
</tbody>
</table>

\[ \Delta(K + U) = W_{\text{added/removed}} \]
<table>
<thead>
<tr>
<th>Variables (include all units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F = \frac{Gm_1 m_2}{r^2} )</td>
</tr>
</tbody>
</table>

### Physics Concept

### Description and Notes

### Diagram
<table>
<thead>
<tr>
<th>Physics Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variables (include all units)</td>
</tr>
<tr>
<td>Description and Notes</td>
</tr>
<tr>
<td>Diagram</td>
</tr>
</tbody>
</table>

\[ \theta = \theta_0 + \omega_0 t + \frac{1}{2} \alpha t^2 \]
<table>
<thead>
<tr>
<th>Variables (include all units)</th>
</tr>
</thead>
</table>

\[ \sum \vec{\tau} = \frac{d\vec{L}}{dt} \]
Physics Concept

Variables (include all units)

Description and Notes

Diagram
Appendix E: Rotational Inertias and Astrophysical Data

Table 10.2 Rotational Inertias

<table>
<thead>
<tr>
<th>Object</th>
<th>Mass $m$</th>
<th>Mean Radius $r$</th>
<th>Orbital Period $T$</th>
<th>Surface Gravity $g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>$m_E = 5.97 \times 10^{24}$ kg</td>
<td>$r_E = 6.37 \times 10^6$ m</td>
<td>$T = 3.16 \times 10^7$ s</td>
<td>$g = 9.81$ m s$^{-2}$</td>
</tr>
<tr>
<td>Moon</td>
<td>$m_M = 7.35 \times 10^{22}$ kg</td>
<td>$r_M = 1.74 \times 10^6$ m</td>
<td>$T = 2.36 \times 10^6$ s</td>
<td>$g = 1.62$ m s$^{-2}$</td>
</tr>
<tr>
<td>Sun</td>
<td>$m_S = 1.99 \times 10^{30}$ kg</td>
<td>$r_S = 6.96 \times 10^8$ m</td>
<td>$T = 6 \times 10^{15}$ s</td>
<td>$g = 274$ m s$^{-2}$</td>
</tr>
<tr>
<td>Physical Quantity</td>
<td>Dimension</td>
<td>SI Units</td>
<td>SI Symbol</td>
<td>In Terms of Other SI Units</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-----------</td>
<td>----------</td>
<td>-----------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>Length</td>
<td></td>
<td>m</td>
<td>BASE UNIT</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td></td>
<td>kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td></td>
<td>s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric Current</td>
<td></td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td>K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amount Of Substance</td>
<td></td>
<td>mol</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Gaussian Units

- Length: cm
- Mass: g
- Time: s
- Electric Current: statampere
- Temperature: K
- Amount of Substance: mol

### SI Units and Conversions

- Work (Energy): J = N·m = kg·m^2·s^-2
- Viscosity (η): Pa·s = N·m^-1·s
- Power (P): W = N·m/s = kg·m^2·s^-3
- Pressure, Stress (Tension): Pa = N·m^-2
- Specific Heat Capacity (C_v): J = kg·K
- Thermal Conductivity (κ): W = m^2·K·s^{-1}
- Torque (T): J = N·m = kg·m^2·s^{-2}
- Vector Potential (A): Wb = m·A
- Velocity (v): m/s
- Viscosity (η): poise
- Work (Energy) (W): J = N·m = kg·m^2·s^{-2}
<table>
<thead>
<tr>
<th>Physical Constant</th>
<th>Symbol</th>
<th>Value(Uncertainty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Mass Unit</td>
<td>amu</td>
<td>1.660 538 782(83) × 10^{-27} kg</td>
</tr>
<tr>
<td>Atomic Unit Of Charge</td>
<td>e</td>
<td>1.602 176 487(40) × 10^{-19} C</td>
</tr>
<tr>
<td>Avogadro Constant</td>
<td>N_A</td>
<td>6.022 141 79(30) × 10^{23} mol^{-1}</td>
</tr>
<tr>
<td>Bohr Magneton</td>
<td>\mu_B</td>
<td>927.400 915(23) × 10^{-20} J T^{-1}</td>
</tr>
<tr>
<td>Boltzmann Constant</td>
<td>k_B</td>
<td>1.380 6504(24) × 10^{-23} J K^{-1}</td>
</tr>
<tr>
<td>Compton Wavelength</td>
<td>\lambda_c</td>
<td>2.426 310 217(33) × 10^{-12} m</td>
</tr>
<tr>
<td>Electron Mass</td>
<td>m_e</td>
<td>9.109 382 15(45) × 10^{-31} kg</td>
</tr>
<tr>
<td>Electron Volt</td>
<td>eV</td>
<td>1.602 176 487(40) × 10^{-19} J</td>
</tr>
<tr>
<td>Faraday Constant</td>
<td>F</td>
<td>96 485 339 9(24) C mol^{-1}</td>
</tr>
<tr>
<td>Fine-Structure Constant</td>
<td>\alpha</td>
<td>7.297 352 537 6(50) × 10^{-3}</td>
</tr>
<tr>
<td>Gravitational Constant</td>
<td>G</td>
<td>6.674 28(67) × 10^{-11} m^3 s^{-2} kg^{-1}</td>
</tr>
<tr>
<td>Impedance (Vacuum)</td>
<td></td>
<td>376.730 313 461 \Omega</td>
</tr>
<tr>
<td>Joule</td>
<td>J</td>
<td>1.112 650 056 × 10^{-17} kg</td>
</tr>
<tr>
<td>Kelvin</td>
<td>K</td>
<td>1.380 6504(24) × 10^{-23} J</td>
</tr>
<tr>
<td>Kilogram</td>
<td>kg</td>
<td>0.009 366 817 4(52) × 10^{-3}</td>
</tr>
<tr>
<td>Inverse Centimeter</td>
<td>cm^{-1}</td>
<td>1.986 445 501(99) × 10^{-27} J</td>
</tr>
<tr>
<td>Molar Gas Constant</td>
<td>R</td>
<td>8.314 472(15) J mol^{-1} K</td>
</tr>
<tr>
<td>Molar Volume Of Ideal Gas</td>
<td></td>
<td>22.413 996(39) × 10^{-3} m^3 mol^{-1}</td>
</tr>
<tr>
<td>Neutron Mass</td>
<td>m_n</td>
<td>1.674 927 211(84) × 10^{-27} kg</td>
</tr>
<tr>
<td>Nuclear Magneton</td>
<td>\mu_N</td>
<td>5.050 783 24(13) × 10^{-27} J</td>
</tr>
<tr>
<td>Permeability (Magnetic Constant)</td>
<td>\mu_0</td>
<td>12.566 370 614 × 10^{-7} N A^{-2}</td>
</tr>
<tr>
<td>Planck Constant / 2\pi</td>
<td>\hbar</td>
<td>6.626 068 96(33) × 10^{-34} J s</td>
</tr>
<tr>
<td>Planck Constant</td>
<td>\hbar</td>
<td>1.054 571 629(53) × 10^{-34} J s</td>
</tr>
<tr>
<td>Proton Mass</td>
<td>m_p</td>
<td>1.672 621 367(83) × 10^{-27} kg</td>
</tr>
<tr>
<td>Rydberg Constant</td>
<td>R_w</td>
<td>10 973 731.568 527(73) m^{-1}</td>
</tr>
<tr>
<td>Speed Of Light (Vacuum)</td>
<td>c</td>
<td>299 792 458 m s^{-1}</td>
</tr>
<tr>
<td>Std Atmosphere</td>
<td>atm</td>
<td>101 325 Pa</td>
</tr>
<tr>
<td>Std Acceleration Of Gravity</td>
<td>g</td>
<td>9.806 65 m s^{-2}</td>
</tr>
<tr>
<td>Stefan-Boltzmann Constant</td>
<td>\sigma</td>
<td>5.670 400(40) × 10^{4} W m^{-2} K^{-4}</td>
</tr>
</tbody>
</table>

**NUMBERS and APPROXIMATIONS**

- \pi \approx 3.141 592 653 589 793 ...
- e \approx 2.718 281 828 459 045 ...
- \hbar \approx 1973.27 eV Å
- m_e c^2 \approx 0.511 MeV
Physics 215 Constants and Equations Sheet

Electric Force (Coulomb) Const  \( k = 8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2} = (4\pi\varepsilon_0)^{-1} \)

Electric Const (Permittivity)  \( \varepsilon_0 = 8.85 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2} = (\mu_0c^2)^{-1} \)

Magnetic Const (permeability)  \( \mu_0 = 4\pi \times 10^{-7} \text{ N A}^{-2} \)

Elementary Charge  \( e = 1.60 \times 10^{-19} \text{ C} \)

Electron Mass  \( m_e = 9.11 \times 10^{-31} \text{ kg} \)

Proton Mass  \( m_p = 1.67 \times 10^{-27} \text{ kg} \)

Planck Const  \( h = 6.63 \times 10^{-34} \text{ J s} \)

**Maxwell Equations**

\[
\int \vec{E} \cdot d\vec{A} = \frac{q_{\text{enclosed}}}{\varepsilon_0} \quad \text{Gauss for } \vec{E} \\
\int \vec{B} \cdot d\vec{A} = 0 \quad \text{Gauss for } \vec{B} \\
\int \vec{E} \cdot d\vec{r} = -\frac{d\Phi_E}{dt} \quad \text{Faraday Ampère} \\
\int \vec{B} \cdot d\vec{r} = \mu_0 I + \mu_0\varepsilon_0 \frac{d\Phi_E}{dt} \\
\]

\[
\vec{F}_{12} = \frac{kq_1q_2}{r^2} \hat{r} \\
\Phi_E = \int \vec{E} \cdot d\vec{A} \\
f\lambda = c \\
\]

\[
\vec{E} = \frac{kq}{r^2} \hat{r} \\
\int \vec{B} \cdot d\vec{r} = \mu_0 I_{\text{encircled}} \\
d\sin\theta = m\lambda \\
\]

\[
\Delta V_{AB} = -\int_A^B \vec{E} \cdot d\vec{r} \\
\vec{F}_B = q\vec{v} \times \vec{B} \\
a\sin\theta = m\lambda \\
\]

\[
\Delta V_{AB} = \frac{\Delta U_{AB}}{q} \\
\vec{\mu} = NI\vec{A} \\
\]

\[
V_{\infty} = \frac{kq}{r} \\
\vec{t} = \vec{\mu} \times \vec{B} \\
\theta_{\text{min}} = \frac{1.22\lambda}{d} \\
\]

\[
I = \frac{V}{R} \\
\varepsilon = -\frac{d\Phi_B}{dt} \\
E = hf = pc \\
\]

\[
P = IV \\
\Phi_B = \int \vec{B} \cdot d\vec{A} \\
\Delta x\Delta p \geq \frac{h}{2\pi} 
\]

xliii
# Physics 110H Course Syllabus

**Physics 110H Journal - 2013-2014**

## KEY:
- **Ø** – Double period;
- **CE** – Conceptual Example;
- **Lab** – Lab Exercise;
- **EP QUIZ** – Exam-Prep Quiz; **CTE** - Critical Thinking Exercise

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**FINAL EXAM**