BODY PHYSICS: MOTION TO METABOLISM

LAWRENCE DAVIS

DEDICATION

For my wife Liz, who continuously teaches by example how to be a great teacher, parent, friend, spouse and human being.

For my children, who continuously teach me perspective and show me how to find wonder in the everyday world.

And for all those great teachers who have dedicated themselves to enriching the lives of students.

CONTENTS

WHY USE BODY PHYSICS?

Fractal Tree by Rafael Ruggiero via Wikimedia Commons

IT'S FREE! AND OPEN! AND ACCESSIBLE!

IT'S DEFINITELY NOT PERFECT, BUT YOU CAN MAKE IT BETTER!

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Join the Open Educational Resource movement and save your students money while providing them with high quality, accessible resources in digital and print formats, all while gaining greater control over your own course resources.

The *Body Physics* format and features were designed with the following considerations in mind, in arbitrary order:

Digital, free and open	Creative commons (CC) license. Digital formats (PDF, ebook, Web Viewing) free to students. Free printable lab sheets included, no separate lab manual to buy.
Low printing cost	No superfluous (curb appeal) images, clean margins. Links to large tables and charts of constants and other data.
Accessible, streamlined, not distracting	In-line diagrams and images containing alternative text, no side-bars or use of margins, basic and consistent heading structure, descriptive links.
Pedagogically sound	Backwards design: Unit outcomes aligned with course outcomes, content and exercises aligned with chapter outcomes. Links to additional resources (articles, texts, simulations, videos, problems with solutions). In-line reinforcement activities provide immediate feedback. Many every-day examples and applications. Structured inquiry-based labs designed to reinforce chapter content and assess learner outcomes. Suggested Personal response system (PRS) questions provided.
Interesting and engaging to students with varied interests	All content is introduced in the context of the human body, then abstracted, generalized, and applied to additional applications.

DESIGN THEORY

With a wealth of information available, introductory textbooks no longer need to serve as sole sources for all course content. However, now possibly more than ever, textbooks may still have an important role in providing students with high quality ***context*** for all of the information floating around out there. Textbooks should also serve as a central hub connecting students to other high quality resources vetted by experts. Finally, textbooks should help students to connect concepts to their own experiences to improve and lengthen understanding. *Body Physics* was created with these roles in mind.

Body Physics sticks to the basic functioning of the human body, from motion to metabolism, as a common theme through which the fundamental physics topics are introduced. This choice allows for a contextual format and narrative quality that connects concepts in different sections and chapters. The common narrative thread does not necessarily prevent individual chapters, sections, or activities from being used as stand-alone content. For example the ***Jolene's Migraines*** example and reinforcement activity could be useful in any science class covering the scientific method. The human body was chosen as the contextual theme so that all students are able to connect with the theme a personal way. For students who are athletes, entering health fields, interested in fitness, struggle with unique physical barriers, or are simply curious about their body, the book should feel particularly applicable.

While many of the existing OER resources are of very high quality, and would be very useful for a variety of courses, most are typically written from the point of view of someone who already possesses a great appreciation for physics. In general terms they are approached with hindsight not held by the student. Even if unconsciously, presentation of content is often driven by appreciation for the elegant universality of fundamental physics concepts, with the goal of bringing similar appreciation to the student. Often the results are general physics concepts presented in an abstract way and then connected to every-day life through examples and application problems. For example, a chapter might be called *Forces and Newton's Laws of Motion,* with sections called *Forces, Newton's First Law, Newton's Second Law, Newton's Third Law*. Of course applications would be provided throughout the sections and the end of the chapter would have likely an *Applications of Newton's Laws* section addressing applications in several different areas of interest, possibly including the human body.

Body Physics attempts to invert the content presentation sequence where logical and integrates the initial presentation of content into a common application theme. For example, the concept of a force is introduced in the Unit titled *Better Body Composition Measurement* using two forces the students have experienced and heard of, namely weight and buoyant force. The unit jumps right into applying these concepts to solving a real-world problem, namely determining body density, and the concepts necessary to solve the problem, such as static equilibrium, are introduced as needed along the way. Generalization of concepts occurs at then end of the unit, or even in a later unit, after concepts have become more familiar and connections between concepts have been discovered. This departure from the standard, highly structured textbook format is only made possible by the quickly searchable nature of digital textbooks such as this one, which allow students to quickly and easily find concepts and definitions embedded in a contextual, even narrative format. As a physicist, and someone who learned from standard textbooks, this departure was not easy. As I worked on an outline for the book, found myself unconsciously falling back into the standard organizational structure (and the one in my own head), before "waking-up" and going back to attempt a reorganization of the material from the point of view of a brand new science student.

HOPE AND HYPOTHESIS

It's exceedingly rare that science textbooks are read word-for-word, and this book won't change that, especially as the number of auxiliary resources available to students grows. However, we do hope that *Body Physics* will increase the amount of time students spend using the textbook to learn and prepare in a pedagogically sound manner. There is no guarantee that the format of body physics will be effective than standard formats and only after observing student performance and receiving feedback from students and instructors will we know if this endeavor was fruitful. Ideally we would like to test the hypothesis: *If the* Body Physics *format is more effective than standard formats, then students using* Body Physics *will perform at a higher level on assessments of learner outcomes than peer students using a standard textbook*. If you would like to collaborate in performing a statistically robust test of such a hypothesis, please contact bodyphysicstext@gmail.com

WHEN TO USE BODY PHYSICS

Body Physics was designed to meet the objectives of a one-term high school or freshman level course in physical science, typically designed to provide non-science majors and undeclared students with exposure to the most basic principles in physics while fulfilling a science-with-lab core requirement. The content level is aimed at students taking their first college science course, whether or not they are planning to major in science. However, with minor supplementation by other resources, such as OpenStax College Physics, this textbook could easily be used as the primary resource in 200-level introductory courses. Chapters that may be more appropriate for physics courses than for general science courses are noted with an asterisk symbol (*). Of course this textbook could be used to supplement other primary resources in any physics course covering mechanics and thermodynamics. The following are an example course description and course outcomes (learner outcomes, learning objectives, etc.) for which Body Physics would be well aligned (see unit outcomes for alignment to course outcomes indicated by [#]):

Elementary concepts of physics including motion, forces, energy and momentum, and thermodynamics. Registration-Enforced Prerequisite MTH 060. 3 lecture, 3 lab hrs/wk.

1. Apply knowledge of the SI units, metric prefixes, and unit conversion factors in solving physics problems.
2. Analyze, rank, compare, and make predictions about qualitative physics scenarios involving motion, forces, energy, momentum and thermodynamics.
3. Analyze and solve quantitative physics problems involving motion, forces, energy, momentum and thermodynamics.
4. Demonstrate proficiency with laboratory equipment, computer software, and experimental procedures for gathering, recording, analyzing and graphing data.
5. Apply the basic scientific method.

HOW TO USE BODY PHYSICS

THE ADOPTION PROCESS

Adopt the entire book or simply use certain content or features to supplement your course materials. If you decide to adopt the book as a required text for your course, consider the following:

- Give plenty of advanced notice to your bookstore to prevent sticking them with expensive unused inventory.
- Work with your bookstore and independent/non-profit printers like Montezuma to provide low-cost print copies for students.
- Check that the textbook content aligns with the course outcomes for your course. The example course outcomes and the Learner Outcomes for each chapter should help with this check.
- Work with your library to get print copies on reserve.
- Provide a link to the book on your LMS. You might consider linking each assigned reading directly to that Unit in the book.
- Ask for feedback from students and record your own feedback to pass on to the author and help to improve the textbook. Send feedback to bodyphysicstext@gmail.com

SUGGESTED USE OF DESIGN FEATURES

Learner Outcomes

- The learner outcomes listed at the beginning and end of each unit provide instructor and student with an overview of what topics will be covered.
- They help the instructor to find section of the book that are applicable their specific course.
- They may help instructors design assessment methods that are specific and relevant while ensuring that course activities are outcome related.
- To aid instructors with adoption, the alignment of the learner outcomes for each unit with the example overall course outcomes is indicated by the number in [brackets] following each outcome.

Everyday Examples

- Everyday examples provide additional context to help students relate to new concepts; some are conceptual and some provide worked examples with answers.
- Everyday examples often make excellent topics for discussion in class or online and less complex instances can be used to inspire reading quiz questions.

Reinforcement Activities

- Reinforcement Activities provide with early-and-often feedback on concepts as they are covered. These activities have now been converted to web-based interactive using H5P in order to provide students with immediate feedback.
- Some Reinforcement Activities are tactile, some are qualitative questions, and some are quantitative.
- The reinforcement activities could be assigned in the place of traditional "homework" and most of class "lecture" time could be used for students to work on the end-of-unit Practice and Assessment problems in groups with instructor help. This hybrid-flipped classroom approach might increase time students spend interacting with the textbook outside of class and is especially useful for courses with under-prepared students.
- Reinforcement activities can be integrated into interactive lectures via polling and games.

Key Terms and Concepts

- The list of key terms and concepts found at the end of each unit can help students to review what they have learned and check their comprehension.
- The list may also help instructors decide which units of the book are applicable to their specific course.
- The list of key terms and concepts is useful to instructors in designing discussion topics, study guides, weekly quiz questions, and conceptual exam questions.
- We hope to eventually have key terms and concepts linked to explanations from external sources, encompassing a variety of media types.

Additional Features and Resources

- **Practice and Assessment Exercises** provide students with practice and instructors with an assessment tool. These problems could be assigned as standard homework problems or group problems in a "flipped classroom" or tutorial session. Please e-mail feedback and suggested improvements to bodyphysicstext@gmail.com
- **Lab** activities are designed to familiarize students with the scientific method and are aligned with learner outcomes. They are located together in a single unit for easy printing. I suggest viewing the labs in a browser and then highlighting, copying, and pasting the entire lab into a word processor to make any necessary changes to equipment and/or instructions, and then printing from the word processor. This will automatically improve print formatting and reduce the paper used in printing. You may want to consider working with your bookstore to provide a printed Lab Manual. After adapting and improving the labs, please share your improved versions with the OER community. You may always e-mail feedback and suggested improvements to bodyphysicstext@gmail.com
- **Design-Build-Test** projects allows students to incorporate their own experience and knowledge into creation of a model system based on the concepts covered in the book.
- **Global glossary** allows for quick reference to definitions of key terms and concepts
- **Links to simulations** from open sources such as Phet provide interactive experience with concepts in the moment or during review.
- **Links to videos** (more soon) from open sources such as Khan Academy provide supplementary explanation to help students with concepts in the moment or during review.

TASKS REMAINING AND COMING IMPROVEMENTS

CONTINUOUS IMPROVEMENT

Body Physics will be subjected to a continuous improvement process. If you would like to contribute content, feedback, edits, or if you have any questions about Body Physics, please e-mail: bodyphysicstext@gmail.com.

RECENT IMPROVEMENTS

1. Creating a global glossary and adding "rollover" action to glossary term
2. Explicit labeling of all Practice and Assessment Exercises with related unit outcome
3. Reordering of chapters to focus locomotion and energy and improve narrative flow
4. Connecting all content introduction to a common character; Jolene
5. Adding student-contributed images and data

ONGOING IMPROVEMENTS

1. convert reinforcement exercises to H5P interactivities
2. Labeling reinforcement activities with related Unit outcome

LONG TERM IMPROVEMENTS

1. Correlate results of statistical analysis of student interaction and performance data to student perception data to identify the most impact changes that could be made to Body Physics.
2. Create a correspondence table showing how sections relate to topics (sections in a standard book)
3. Create at content map, (mind map, content web). Open Pedagogy Exercise?
4. Adding and improving reinforcement activities, everyday examples, and practice exercises
5. Internal Linking
6. Solutions to Reinforcement Activities
7. Solutions to Practice and Assessment Exercises
8. Compiling a conceptual question bank
9. Tabulate links to vetted external resources (text and video) for all key terms and concepts
10. Chapter-specific video lectures w/ demonstrations
11. Concept-specific Algodoo simulations and activities

WHO CREATED BODY PHYSICS?

The following people were instrumental in the creation of Body Physics as an Open Education Resource. Body Physics would not have been created without their efforts. Sole responsibility for errors, including but not limited to, grammatical, typographical, technical, attribution, format, and export errors, lies with the author.

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Dr. Lawrence (Mick) Davis is an Associate Professor of Science at Umpqua Community College (UCC) in Roseburg, OR where he teaches General Physical Science, General Physics, General Physics with Calculus, and Water Resource Science. In his spare time Mick enjoys alpine climbing, volunteering with Eugene Mountain Rescue, working with UCC's wrestling teams (men and women), participating in outreach activities such as STEAMHub, and now writing OER textbooks. Mick's interests in STEM education and in body physics were both sparked by his time at Pacific University where he earned a B.S. in Physics and a top-10 national ranking in wrestling. Mick's body physics interest continued through graduate school at the University of Oregon (UO) where he earned a Ph.D. in physics and traded wrestling for climbing as an excuse to get out of the lab. Mick's research focused on the growth, morphology, and optical properties of metallic nanostructures, but he also worked on a collaborative project with the Oregon Institute of Neuroscience and started a consulting company to fulfill a local industry need for physical modeling of stream temperature. The UO is also where Mick met his wife Liz, who is an R.N. and clinical instructor for the Nursing Program at UCC. Raising their two young children has reduced time spent climbing, but provided a whole new source of interest in both neuroscience and the physics of the human body.

PART I.

UNIT 1: PURPOSE AND PREPARATION

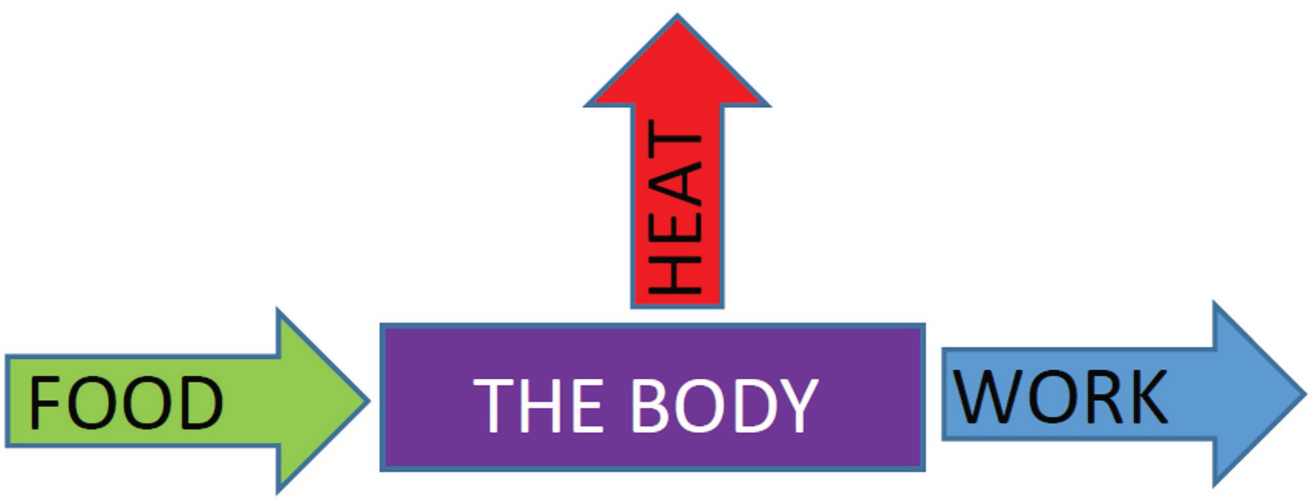
Unit 1 Learner Outcomes [No specific alignment with example course outcomes]

1. State the most basic purpose of the human body from a physics viewpoint.
2. State the purpose of this textbook.
3. Identify barriers to academic success and evaluate strategies to overcome barriers.
4. Explain the course expectations, including cognitive level and time commitment.
5. Provide an example study strategy that incorporates feedback and metacognition.

CHAPTER 1.

THE BODY'S PURPOSE

In order to accomplish your goals in life you must do a lot of work. Not work in the economic sense, but work in the scientific sense, which means to transfer energy from one form to another by application of a force over some distance. The purpose of this work includes, but is not limited to; the regulation of temperature, maintaining chemical concentrations, blood circulation, breathing, nerve impulse production, physical movements, and manipulation of environmental objects. A side-effect of doing all this work is the production of thermal energy which you release to your environment as heat. The combination of doing work and generating heat depletes your internal energy reserves, requiring you to take in more chemical energy (food). The purpose of the human body is to facilitate the body's energy pathway, (energy input, energy storage, work output, and heat release), in order to maintain the conditions necessary for life and allow you to accomplish those things which are important to you.

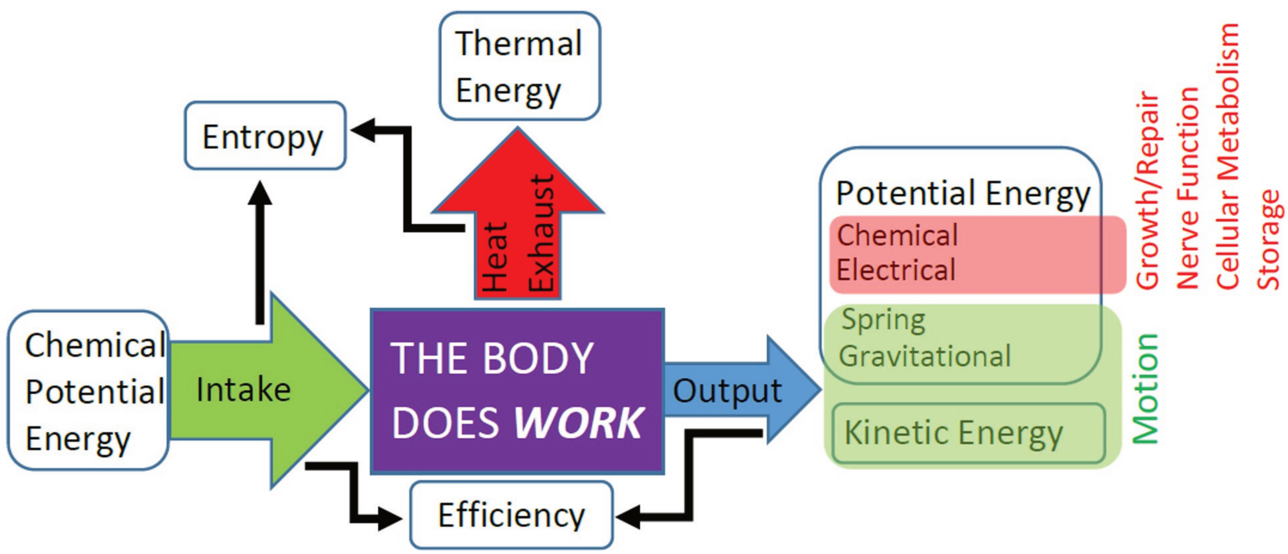


The basic energetic functions of the human body. This book will discuss the physics concepts behind this diagram, in addition to many others. The diagram will acquire more detail as we go along, eventually morphing into the complete concept map shown in the next Chapter.

CHAPTER 2.

THE PURPOSE OF THIS TEXBOOK

In order to understand why living requires work, and exactly how you get that work done, we need to understand the concepts of work, energy, and entropy. These happen to be some of the most fundamental concepts in all of physics. This textbook will introduce you to these fundamental concepts by analyzing the functioning of your own body. Along the way we will also learn about other physics concepts that help us to understand how we move, respond to forces, sense changes to our environment, and manipulate objects.



The most basic functions of the human body mapped to the main concepts covered in this text. Many of these terms might be new to you, but don't worry, this is just a preview. Later you will examine the similarities between this type of diagram for the human body and that of heat engines, such as the internal combustion engines, which power most vehicles.

CHAPTER 3.

PREPARE TO OVERCOME BARRIERS

Everyday Example

This term Jesse is taking two online courses and a face-to-face science course with a lab, so he will need to be on campus four days per week. Jesse lives and works in a rural area 20 miles from campus and there is no bus system between his home and campus. Jesse has a vehicle, but it's not very reliable and he expects that he won't make it through the term without a breakdown. Most of his money will go to tuition, gas and rent so Jesse does not have money available for a new vehicle, but he is usually able to make minor repairs within a few days when breakdowns happen to keep the vehicle running. Jesse has identified a breakdown as a possible barrier to his academic success, but he doesn't want to let that barrier stop him. Jesse is brainstorming things he can do now in preparation for meeting and defeating this barrier. Do you have any ideas?

Reinforcement Exercises

You are completely capable of being successful at physics, but that success will not come without time and effort. Life will present you with barriers to success and some of those barriers will not be under your control. You may not be able to remove them, so you will need to work with your instructor, advisor, family, and co-workers to find ways to get over, under, around, or straight through them. The information following sections and the activities at the end of the chapter will help you to define what success in this course means to you and identify barriers to that success. The activities will also prepare you to most efficiently apply your valuable time and effort to achieving your success.

An interactive or media element has been excluded from this version of the text. You can view it online here:
https://openoregon.pressbooks.pub/bodyphysics/?p=181

CHAPTER 4.

PREPARE TO STRUGGLE

The goal of science is to find answers to questions. In order to accomplish that goal, scientists discover questions we don't have answers for, figure out what work needs to be done to find the answers, and then do that work. We will examine the scientific process in more detail at the end of chapter two, but essentially doing science means starting out confused and then thoughtfully struggling through steps necessary to become unconfused. That also happens to an effective approach for in-depth learning on many topics[1].

Everyday Example

Jamie works at a small business owned by a family friend. The owner told Jamie that another friend used a spreadsheet to track the budget for his own business and that it was helpful in keeping costs down and doing taxes. Jamie's boss assumed that because she was young she would be good with computer stuff so he offered Jamie some extra pay to make a spreadsheet and start tracking the budget for the business. Jamie was excited about the extra pay and putting budget management on her resume, and she wanted to impress her boss, but she had never worked with spreadsheets before and that worried her. Jamie decided she would just have to learn, and quickly. Jamie found a free spreadsheet program online and tried working with it, but it was too complex to figure out by trial and error and she felt frustrated that she was wasting time. In order to get the sheet done as quickly as possible Jamie tried searching the program's help feature for the specific operations she wanted to do, but she didn't even really know what words to search for. Also, it felt like the help pages were written for someone who already knew the basics of the program and it was a struggle to follow the examples. Jamie thought it wouldn't take long if she asked some of her friends who were into computer stuff for help, but they just ended up taking the mouse and doing things for her with little explanation and too fast for her to follow along or remember later. Jamie did get some parts of the sheet completed quickly this way, but she didn't learn much and wouldn't be able to finish, adapt, or improve the sheet on her own. Jamie worried that she might make a mistake in the budget later on if she relied too heavily on her friends. Jamie was really frustrated, but not yet ready to give up. Jamie searched the web for help with spreadsheets and found some video tutorials. It took some time to figure out which videos were for beginners, but she eventually found some. Being able to pause the video and repeat the operations in her own spreadsheet was slow, but really helpful. After a couple of hours she understood the basics of the program and had built a simple budget spreadsheet. As she worked to adapt her program to her specific business Jamie found that she could now effectively use the help feature of the program, which allowed her to make a lot of progress. Jamie was able to add a function that automatically updated and graphed the business profits when new payments and expenses were added and that moment

1. "The Importance of Failure in Learning" by David Freyberg, Tomorrow's Professor , Stanford University

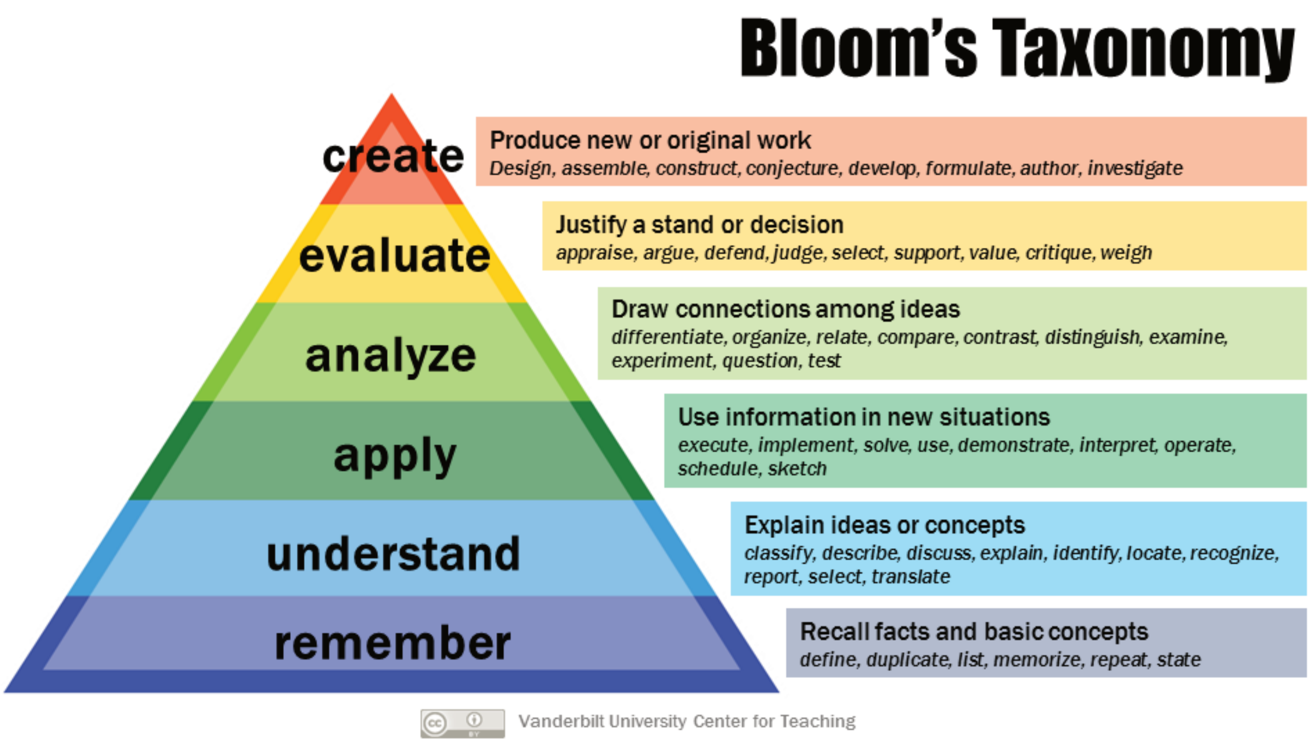
felt really great. Jamie wanted to add some fancy features to really impress her boss, and asked her friends for help. Jamie found that now she could usually follow along and had the confidence and the language to ask questions when she couldn't. In addition to creating an efficient spreadsheet and picking up a useful skill, Jamie learned that there isn't really a shortcut to learning something complex. Knowing that hard work and perseverance will be required, Jamie can actually save time by not trying to avoid the difficult and sometimes slow learning process.

Until the science fiction of implanting information directly into the brain becomes reality, we must all experience some amount of confusion, struggle and discomfort during any learning process, including during this course. Rather than fear struggling and being confused, recognize that when you are struggling is a part of in-depth learning. If you avoid struggling with a topic, you may learn it at a shallow level, but you avoid learning it in depth. Embrace your struggles in this course as an indicator that you are learning. Enjoy the *ah-ha!* moments of becoming unconfused.

CHAPTER 5.

PREPARE YOUR EXPECTATIONS

This course is an introductory level science course, which typically means the students are expected to remember, understand, apply, and at times analyze the concepts covered in the course. These expectations correspond to the first four levels of Bloom's Taxonomy, a tool for categorizing thinking and learning, also known as cognition. Further into your academic timeline you will take courses with higher numbers and greater focus on the upper levels. However, to better prepare you for success in a complex world, this course may also use guided projects to expose you to the higher level cognitive processes.



This course focuses on the lower portion Bloom's Taxonomy, but at times you will have the opportunity to analyze, evaluate, and create. Be sure to use your instructor as a resource while working at any cognitive level.

1

The following table uses the concept of conservation of energy to illustrate of how students might be expected to participate in each level of Bloom's Taxonomy within an introductory physics course.

Remember	Memorize a small number of basic physics principles or laws, such as the law of conservation of energy.
Understand	Explain how conservation of energy puts limits on what your body can do physically
Apply	Use the law of conservation of energy to figure out how fast you would be moving after falling from a two story window.
Analyze	Use the conservation of energy to distinguish between possible and impossible results. Do experiments in the lab to test the law of conservation of energy.
Evaluate	Use conservation of energy to evaluate the likelihood of truth behind claims made by various diet and exercise plans.
Create	Design and construct models of sections of the human musculoskeletal system and use the law of conservation of energy to predict how they will behave.

Connection of cognitive levels to various actions performed in this course.

Reinforcement Exercises

An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=204

1. "Blooms Taxonomy" by Vanderbilt Center for Teaching and Learning is licensed under CC BY 4.0

CHAPTER 6.

PREPARE YOUR STRATEGY

~~MULTITASKING~~

Humans can complete more than one simple task at one time, which is called multitasking. For example if you were to walk and chew gum you would be multitasking. However, multitasking when one or more of the tasks are even slightly complex rarely saves time and usually results in lower quality outcomes.

Reinforcement Activity

Use a stopwatch to time yourself while you write down each letter of the alphabet in a row and then below that write each number from 1-26 in a row. Record your time on your paper.

Next you will recreate the same two rows of letters and number as before, only this time you will write a letter on the top row, then a number below, then a letter above, and so on. You've already done this once so if multitasking really is more efficient then you should be faster this time. Record your time for this trial.

Were you faster when multitasking? Was the quality of your work higher?

Don't multitask when studying. Spend at least twenty minutes of focused work on a single topic, then take a few minutes of relaxed reflection on your work before moving on to a new task. Even listening to music might be distracting if you are actively listening to the lyrics or trying to decide if you like the song. If you notice yourself thinking about the music and not the subject you are studying, you may need to try something new.

FEEDBACK

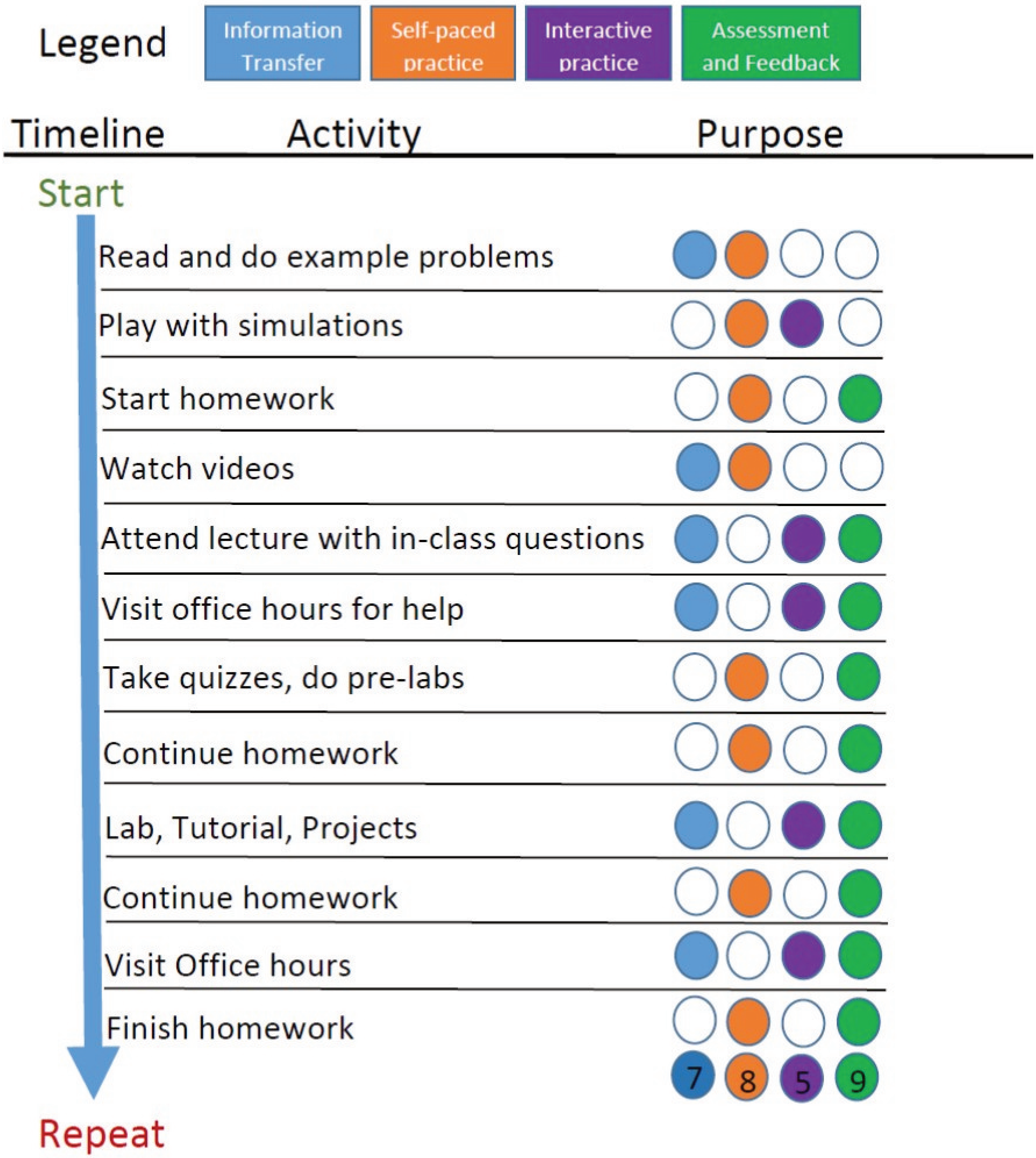
While new to a topic you don't yet have the tools to correctly evaluate your own progress toward understanding. Put simply, ***when first starting out you don't know what you don't know, which can lead to overestimating your level of preparation*** until after an exam or other heavily weighted assignment. Receiving feedback on your progress early and often will help you to avoid this barrier to success. Your instructor might provide early and often feedback in the form of quizzes, online homework, tutorials, in-class practice problems, and clicker questions, to name a few. You should actively seek out early and often feedback by attempting the example problems in the book before looking at the solutions, starting your homework early, and asking questions during your instructor's office hours.

In order to make the most of the feedback you receive you should practice metacognition. In other words, don't just think, also think about how you are thinking[1]. When learning something new, consider why you are going to learn it. Make a plan for how to learn it. Assess your progress in learning it and identify ways to improve your plan. When you think you already know something, stop and ask yourself how, why, and when you came to know it. Reflect on what information that knowledge is based, where the information came from, and how you might verify the information. Metacognition can help you recognize when you don't yet have enough information to make a good decision, so it might significantly improve your learning and help you avoid barriers to success, both in school and in life. For more information check out this detailed resource on metacognition.

STUDY STRATEGY

You should adopt a study strategy that avoids multitasking, but includes early and often feedback along with meta-cognition (just by reading this section you are already engaging in light metacognition). Start by first attempting to understand concepts with aid from various resources. Assess your knowledge by applying it to new situations, and then use the assessment results for metacognition. Seek help from your instructor on concepts that aren't yet clear. Review material that you figured out you don't yet know, and then repeat. The various activities in your courses are already structured to facilitate exactly that process. The diagram below is an example study cycle that would likely be effective in most science courses. Notice that the majority of activities provide feedback. Anytime feedback is provided you should employ metacognition and evaluate the effectiveness of your study methods. The chart that follows gives specific tips on maximizing the impact of each part of the cycle.

1. "Metacognition" by Nancy Chick, Vanderbilt Center for Teaching and Learning is licensed under CC BY 4.0



Effective study cycle. the color coded legend bubbles indicate the purpose behind activities in introductory courses. The totals at the bottom indicate the number of activities that fulfill each purpose. Notice that most activities provide some form of feedback that can be used in a metacognitive process.

WATCH	Write down questions about what you didn't understand. Write down words and concepts that seem important so that you can look for those during lecture and while reading.
ATTEND	Attend lectures and pay attention. Ignore your phone and stay awake. Try **not** to take comprehensive notes. Instead actively process lecture material by relating it to your own experiences, anticipating the instructor's next move, participating in practice calculations, and asking questions. Only write down the most important and most confusing ideas so you can revisit them later.
READ	Use the textbook/instructor's notes as your primary resource, not your own notes. Read the chapter outcomes so you know what you are expected to learn Look up words you don't know and write down questions you have so you can ask during lecture or office hours. Look out for the concepts you wrote down from videos and lecture. Don't skip example problems and example scenarios. If a question is asked, stop and answer it out loud or in writing.
ASSESS	Do what you can to contribute equally to labs and projects. Check to see if you can explain to others how lab activities and projects are related to specific concepts. Try to solve example problems in the book without looking at the solution first. Start your homework early. See how far you can get on your own before asking for help. Use this as an indicator of gaps in your knowledge. Ask your instructor or a tutor for homework help before asking classmates. They will help you fill in knowledge gaps differently than classmates will. Work on homework with your classmates. Don't look at solutions from classmates who are already finished or solutions posted/provided on-line. These will prevent you from accurately evaluating your level of preparation. Take in-class questions and quizzes seriously. Use your scores to tell you what you need to study again. Check your overall grade often and talk with your instructor about your progress and your goals.
ADJUST	Use your exam and overall grade to determine if your study strategy is working. Ask your instructor for help making adjustments if it's not.
REVIEW	Use the results of your evaluations to determine what specific material you need to review and ask your instructor about.

REPEAT	Repeat this cycle for each week, chapter, module, or other method of organizing material used by your instructor. You should also repeat the previous three steps prior to an exam.

CHAPTER 7.

PREPARE YOUR SCHEDULE

We now see that applying an effective study cycle takes time and effort. Most students find that college academics requires significantly more time and effort than high school academics. The difference in time and effort expectations between new students and instructors sometimes creates a barrier to success. Avoid this barrier by talking with your instructor about their expectations. Then follow the numbered instructions below to create a schedule to help you determine what time you have available to study. Your school may use an online learning management system (LMS) such as CANVAS or Blackboard, which probably has a scheduling feature that automatically populates your courses so all you have to do is add in your other commitments and study time. Otherwise, just use your favorite calendar app or planner, or print off a free weekly planner, or ask your instructor for help creating your schedule using a spreadsheet, or try one of these free online schedulers designed for college students:

https://freecollegeschedulemaker.com/
https://www.mystudylife.com/
https://www.canva.com/create/weekly-schedules/

Reinforcement Activity

1) First enter the obligations you already have, such as work, other classes, family obligations, athletic practices, and any others into your planner.

2) Next, find out how much time you will be expected to spend on each course outside of the classroom. The time will depend on the class level (number), the course credits, and your preparation and familiarity with the subject matter. Your instructor will be able to help you estimate this time.

3) Finally, incorporate your effective study cycle into your schedule. Identify time in your schedule to complete each part of your study cycle.

4) Also schedule time for other things that may be important to you, such as exercise or time with friends. If there isn't

enough time for everything, you will need to prioritize. Simply neglecting some of your obligations is not a good strategy and will not lead to success.

5) If you discover that you are short on time and some prioritization is necessary, work with your instructor and your advisor, as well as family and work, to ensure that you have enough time to meet all of your obligations.

CHAPTER 8.

UNIT 1 REVIEW

Key Terms and Concepts

- Energy Pathway
- Barriers
- Cognition
- Blooms Taxonomy
- Multitasking
- Feedback
- Metacognition
- Study strategy

Unit 1 Learner Outcomes [No specific alignment with example course outcomes]

1. State the most basic purpose of the human body from a physics viewpoint.
2. State the purpose of this textbook.
3. Identify barriers to academic success and evaluate strategies to overcome barriers.
4. Explain the course expectations, including cognitive level and time commitment.
5. Provide an example study strategy that incorporates feedback and metacognition.

CHAPTER 9.

UNIT 1 PRACTICE AND ASSESSMENT

Outcome 1

1) Diagram the energy pathway of the human body at the most basic level. Label each of the three basic processes with an example from earlier today of how that process happened for you.

Outcome 2

2) State three basic concepts studied in physics and covered in this textbook.

3) Browse the table of contents and state which topic covered by this book looks most interesting to you and why.

Outcome 3

4) Identify three possible barriers to your academic success.

5) Provide a possible solution to each of three barriers to academic success.

Outcome 4

6) Identify at least two important differences in academic expectations and/or academic structure between high school and college.

7) What is the highest level of cognition at which you have operated? Was it at home, school, work, or during military service? Explain the situation using terms from Bloom's Taxonomy.

8) Explain how you acquired the experience, skills, and knowledge necessary to operate at the cognitive level you described in the previous question. Were you born with it, just acquire it suddenly one day, or did you acquire it gradually over time? Did it take effort or was it easy?

Outcome 5

9) Apply metacognition to some information from outside this course that you might already understand. State the information, explain how you applied metacognition, and then explain how metacognition affected your original understanding.

10) Build your personal study strategy for this course. The strategy should include activities like reading, working examples, video watching, homework, office hour visits, exam preparation, etc.

a) First enter the obligations you already have, such as work, other classes, family obligations, athletic practices, and any others into a planner.

b) Next, find out how much time you will be expected to spend on each course outside of the classroom. The time will depend on the class level (number), the course credits, and your preparation and familiarity with the subject matter. Your instructor will be able to help you estimate this time.

c) Finally, incorporate your effective study cycle into your schedule. Identify time in your schedule to complete each part of your study cycle.

d) Also schedule time for other things that may be important to you, such as exercise or time with friends. If there isn't enough time for everything, you will need to prioritize. Simply neglecting some of your obligations is not a good strategy and will not lead to success.

e) If you discover that you are short on time and some prioritization is necessary, work with your instructor and your advisor, as well as family and work, to ensure that you have enough time to meet all of your obligations.

PART II.

UNIT 2: MEASURING THE BODY

Unit 2 Learner Outcomes

1. Describe the scientific method through an original example of how it could be applied to the student's everyday life. [5]
2. Identify the differences and relationships between empirical models, physical models, hypotheses, theories, and laws. [5]
3. Find necessary conversion factors and convert between SI and non-standard units for several physical quantities. [1]
4. Perform order of magnitude estimation. [2]

CHAPTER 10.

JOLENE'S MIGRAINES

Jolene is a Registered Nurse (RN). After taking time off to have her first child she returned to work. She *observed* that she had migraines of varying severity every time she worked a twelve hour shift. She was able to fight through the migraines and do her job, but it was difficult, painful, exhausting, and possibly dangerous.

Jolene wondered what was causing the migraines. To answer this *question* she *gathered available knowledge* from friends and co-workers, the internet, and her health care provider. These sources gave many possible reasons for migraines[1]. Jolene had taken science courses in preparation for nursing school, so she knew the best way to determine the cause was to use the scientific method. She evaluated the list and eliminated the possible test conditions that didn't apply or that she couldn't change:

Jolene's Table of Possible Migraine Causes

Possible Cause	Reasoning	Readily Testable?
Dehydration	*she rarely had time to stop for water during shift*	Yes
~~Caffeine withdrawal~~	*she drank coffee at work*	No
~~Changes in hormone levels~~	*she was breastfeeding, but didn't want to stop*	No
Changes in sleep patterns	*she did go to bed and get up earlier for shifts*	Yes
~~Drinking alcohol~~	*she didn't drink*	No
~~Exercise or other physical stress~~	*on her feet 12 hours, but no control of that*	No
~~Loud noises or bright lights~~	*the hospital lights are bright, but no control*	No
Missed meals	*she often didn't have time to eat meals on shift*	Yes
~~Odors or perfumes~~	*no control of the hospital smells*	No
~~Smoking or smoke exposure~~	*not in the hospital*	No
~~Stress and anxiety~~	*definitely, not much control*	No
~~Certain foods~~	*she missed meals, but didn't eat different foods*	No

Each of the three variables remaining on the list could be tested, so each one could be used in a hypothesis. One-by-one Jolene would hypothesize that a test condition was the cause and then test the hypothesis by changing only that one condition and observing how it affected her migraine. For

1. "Migraine" by U.S. National Library of Medicine

example her first stated hypothesis could be: *dehydration is contributing to my migraines.* Her first test could be to stay well hydrated and observe how it affected her migraines. Sometimes it's easier to compare results with a null hypothesis, which in this case would be: *hydration level does not affect my migraines.*

Jolene realized that more than one variable could be contributing to her migraines, and that changing one might only affect the severity of her migraines rather than prevent them, so she needed to do more than just observe, she needs to make a *measurement* of migraine severity. She decided to use the Wong-Baker 1-10 Pain Scale as her measurement tool (instrument). She calibrated the scale with childbirth on the top, no pain on the bottom, and stepping on a Lego in the middle.

Finally, Jolene decided she would make multiple tests of each hypothesis by rotating through them. First, she kept track of her scores for the first week, but didn't change her behavior. This was the first control week. The next week she made sure to drink more water, followed by a week of going to bed and getting up at the same time every day, and finally she made sure to have quick foods ready for breaks all of the third week. Jolene repeated the cycle for 12 weeks, and kept track of her data in a table. To analyze the data she and added up the pain scores for the three shifts each week and put those results into a table.

Table of Jolene's Weekly Pain Scale Totals

Test Condition	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Total
Control	25				22				27				
Hydration		24				26				21			
Consistent Sleep			18				20				19		
Nutrition				23				27				25	

Reinforcement Activity

Just as we saw from Jolene's example, the basic scientific method is: *Observe,* ask a *question*, formulate a hypothesis, use the hypothesis to make a *testable prediction*, *test* the prediction experimentally, analyze results, *compare* prediction to test result, and formulate a conclusion.

This example is based on actual events, but names have been changed. The real-life Jolene concluded that a consistent sleep schedule was the most important factor. She then committed to getting up every day at the same early time as she did on works days, even if she didn't have work. After about three weeks her migraines leveled out at about one low-severity migraine per month.

Most of the information that we use in this textbook, from the amount of force that bones can

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support to the amount of energy contained in various foods, was determined by scientists using the scientific method, but maybe not in exactly the same way that you learned in middle school.

CHAPTER 11.

THE SCIENTIFIC PROCESS

SCIENCE AS A CYCLE

The scientific method alone is not enough to make real progress in accumulation of scientific knowledge, but using it as the hub of a cyclic process has led to the massive rate of scientific and technological advancement we have seen over the last century. Science can be thought of as a continuous process guided by with the scientific method as discussed in the following video:

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Reinforcement Exercise

Modern science is done according to a complex process of checks and balances, such as replication and peer-review. This complexity emerged to help ensure the integrity of scientific results, but the process remains rooted in the basic scientific method. You can apply the basic scientific method every day, just as Jolene did, in order to ensure that you make informed decisions that aren't overly biased by inaccurate data, false logic, or your own preconceptions.

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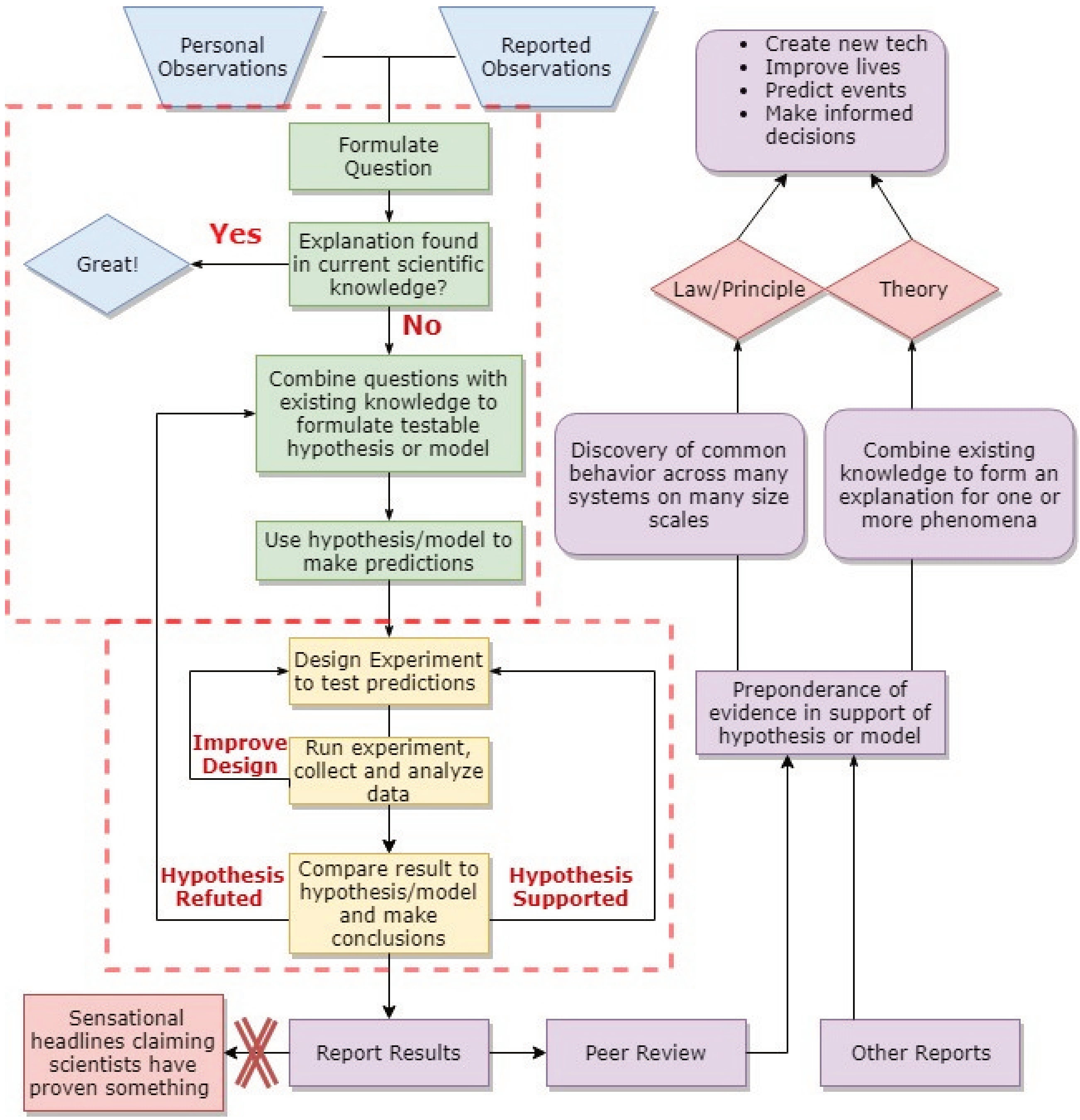

The complex modern scientific process built around the basic scientific method (within dashed lines).

The previous diagram illustrates the complex scientific process, but also highlights the basic scientific method that Jolene used in the previous example, on which the whole process is built. After observation, the basic scientific method follows the green and yellow boxes within the dotted line in the diagram below. Generally speaking, the green boxes comprise theoretical science and the yellow boxes comprise experimental science. These days most scientists participate in some or all parts of both categories and collaborate with other scientists to complete the process.

The uncertainty associated with all measurements means that science cannot *prove* anything, despite what the media often claims. Instead, the scientific process produces reviewed and reproduced conclusions that account for uncertainty. (We will learn how scientists recognize and deal with uncertainty in the next chapter). Scientific conclusions provide evidence for or against hypotheses.

LAWS, PRINCIPLES AND THEORIES

LAWS

When a certain behavior is repeatedly observed across many systems of many sizes and time periods, then the behavior becomes a law. A law is not an *explanation* of the observed behavior. For example, the 1st Law of Thermodynamics states that the when a system does work and/or loses heat, the internal energy of the system must drop by an amount equal to the work done plus the heat lost.

PRINCIPLES

Principles summarize rules created based on collections of laws and followed by scientists when formulating hypotheses, designing experiments, analyzing results. For example, the principle of conservation of energy states that energy cannot be created or destroyed, only transferred. The 1st Law of Thermodynamics supports the principle of conservation of energy.

THEORIES

When a preponderance of evidence supports a particular *explanation* for observed occurrences (phenomena), then the explanation becomes a theory. Laws, principles, and theories are what the general public and media often refer to as scientific facts, but we don't need to introduce another definition so we won't use fact here. We will combine and apply a variety of laws, principles, and theories to understand how the body functions.

Reinforcement Exercises

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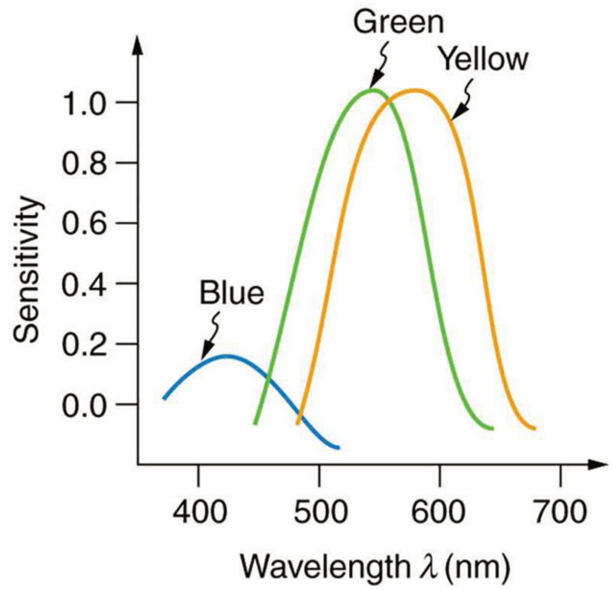
CHAPTER 12.

SCIENTIFIC MODELS

PHYSICAL AND EMPIRICAL MODELS

A model is a representation of something that is often too difficult (or impossible) to observe or display directly. Although a model is justified by experimental tests, it is only accurate in describing certain aspects of a physical system. For example, a basic model of color vision which accounts for the response of the eye to different colors, but not for the processing of that information by the brain[1]Such a model is not all-encompassing, but it is still useful in many situations, such as designing digital displays or creating a computer simulation to predict the results of various color combinations. Check out this interactive simulation of color vision.

1. [1] OpenStax University Physics, University Physics Volume 1. OpenStax CNX. Jun 5, 2018http://cnx.org/contents/d50f6e32-0fda-46ef-a362-9bd36ca7c97d@10.16.



The graph shows the relative sensitivity of the three types of cones, which are named according to light wavelengths (colors) of greatest sensitivity. Evidence for the three types of cones comes from direct measurements in animal and human eyes and testing of color blind people. Image Credit: OpenStax College Physics

Widely applicable Physical models (mechanistic models) that explain how a system works, like the color vision model, can become theories after a preponderance of evidence has been built supporting their validity. Empirical models, which use mathematical trends in observed data, cannot become theories, but they are still useful for making decisions once they have sufficiently been validated.

QUALITATIVE AND QUANTITATIVE MODELS

Both physical and empirical models can be either qualitative or quantitative. Qualitative models predict what behavior you expect to observe, while quantitative models predict behaviors to observe and actual values of measurements. The following table will help you understand the different types of models. The amount of information provided by the model increases as you move from upper left to lower right of the table.

Examples of Models to Explain Observations of Falling Objects.

	Empirical	**Physical (Mechanistic)**
Qualitative	In the absences of air resistance, objects dropped from the same height will hit the ground at the same time, no matter what the objects are.	When you drop something it falls due to mutual gravitational attraction with the Earth. More massive things feel a greater attraction, but they are also more difficult to accelerate, so everything ends up accelerating at the same rate.
Quantitative	Without air resistance, everything falls with the same acceleration value of 9.8 **m/s/s**.	Combining Newton's Law of Universal Gravitation and Newton's 2nd Law of Motion, to predict that the free-fall acceleration for objects at the surface of the Earth should be 9.8 **m/s/s**. (And it is!).

Stay tuned, the Unit 2 lab will produce a *quantitative empirical model* for the fall time of certain objects from a certain height when air resistance is present.

COMPUTER MODELS

Computer modeling is a relatively new tool for science, but it still fits right into the overall process. Computer models are often used to assist in making predictions to be tested experimentally. Sometimes computer models are used as surrogates for expensive, time consuming, or complex, experiments to inform the experimental design process. However computer models are not permanent substitutes for experimentation and the results of computer models should be verified by experimentation or observational data. Computer models which have been verified against data are exceptionally helpful in making predictions used in decision making. For example modeling high altitude winds to plan airliner flight paths and modeling storm paths to plan emergency procedures.

Reinforcement Exercises

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CHAPTER 13.

MEASURING HEART RATE

UNITS

Working as a nurse, one of the most common measurements Jolene takes is heart rate. Heart rate is often measured by counting the number of pulses that occur in the wrist or the neck over a specified amount of time. In order to compare heart rates measured by different people we need to be sure that everyone is using the same measurement units. The medical field uses beats per minute (**BPM**) as the standard unit for heart rate measurements.

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UNIT CONVERSION

Rather than waiting and counting pulses over a full minute, you can make the measurement more quickly by counting pulses for six seconds and then multiplying the number by ten, to get the number of pulses that would have occurred in sixty seconds, or one minute. This process is known as *unit conversion* and the number ten was the conversion factor for this example.

Everyday Example: Heart Rate

Carlotta wants to determine her heart rate in **BPM**. She counts nine pulses in six seconds. She then uses a conversion factor of ten to convert from beats per six seconds to **BPM** and determines her heart rate to be 90 **BPM**:

$$(9\,beats\,per\,six\,seconds) \times 10 = 90\,\mathbf{BPM}$$

The chain-link method of unit conversion prevents mistakes by keeping track of all the values, units, and conversion factors.

To apply the chain-link method:

1. Write down the original value and units.
2. Set this equal to itself, only now with units written as a fraction.
3. Multiply by conversion factors to cancel undesired units and leave only desired final units.
4. Invert some conversion factors to get the undesired units to cancel, if needed.
5. Multiply the numbers across the top.
6. Multiply the numbers across the bottom.
7. Divide the top result by the bottom result.
8. Record the final value.
9. Add on the desired final units (top and bottom) that are left over after cancelling.

Applying the chain link method to the previous example gives us the same answer, only now we don't need to just know ahead of time that we should multiply by ten, we only needed to know there are 60 seconds in one minute, which we use as our conversion factor.

Everyday Example: Heart rate

Carlotta wants to determine her heart rate in **BPM**. She counts nine pulses is in six seconds. She then uses a conversion factor of ten to convert from beats per six seconds to **BPM** and determines her heart rate to be 90 **BPM**:

$$9\,beats\,per\,six\,seconds = \frac{9\,beats}{6\,\cancel{seconds}}\left(\frac{60\,\cancel{seconds}}{1\,minute}\right) = \frac{9\,beats \times 10}{minute} = \frac{90\,beats}{minute}$$

$$= 90\,\mathbf{BPM}$$

Applying the chain link method to the previous example gives us the same answer, only now we don't need to know ahead of time that we should multiply by ten, we only needed to know that were 60 seconds in one minute, which we used as our conversion factor.

The act of ensuring that your answer to a problem has the correct units is called unit analysis. The term chain-link method is often used interchangeably with the terms unit analysis or dimensional analysis, such as in this helpful video demonstrating unit analysis with the chain-link method. Let's practice some more unit conversion using the chain-link method with multiple conversion factors:

Everyday Example

Ronnie wants to estimate how much money he will spend on gas driving back and forth from campus this term. A round-trip to campus is 14.2 miles, his car typically gets 27 miles per gallon (**MPG**) and gas is currently **$**2.86 per gallon. He needs to drive to campus and back four times per week. Let's predict his cost for gas during the 11 week term.

$$11\, weeks\, per\, term = \left(\frac{11\, weeks}{1\, term}\right)\left(\frac{4\, trips}{1\, week}\right)\left(\frac{14.2\, miles}{1\, trip}\right)\left(\frac{1\, gallon}{27\, miles}\right)\left(\frac{2.86\, dollars}{1\, gallon}\right)$$

$$= \left(\frac{66.18\, dollars}{1\, term}\right) = 66.18\, Dollars\, per\, term$$

STANDARD UNITS

Similar to medical professionals, scientists use standard scientific (SI) units when reporting measurements so we can all stay on the same page. For example, the fundamental SI unit of time is seconds. In this course we will primarily use seconds for time, meters for length, kilograms for mass, and Kelvin for temperature. All of the other units we use will be combinations of these few fundamental SI units. The table below shows all seven of the fundamental SI units and their abbreviations[1]. All other standard scientific units are derived units, meaning they are combinations of those seven fundamental units. Throughout this book abbreviated units will be **bold** for clarity. The seven fundamental units and their abbreviations are summarized in the following table. Visit the National Institute for Standards and Technology (NIST) for more information on standard units.

Table of the fundamental International Standard (SI) units

Property	Unit	Abbreviation
Length	meter	**m**
Mass	kilogram	**kg**
Time	seconds	**s**
Number (Amount)	mole	**mol**
Temperature	Kelvin	**K**
Electrical Current	Ampere	**A (amp)**
Luminous Intensity	candella	**cd**

As with heart rate, the standard medical units and standard scientific units don't always match up,

1. Abozenadah, H., Bishop, A., Bittner, S., Lopez, O., Wiley, C., and Flatt, P.M. (2017) Consumer Chemistry: How Organic Chemistry Impacts Our Lives. CC BY-NC-SA. Available at: http://www.wou.edu/chemistry/courses/online-chemistry-textbooks/ch105-consumer-chemistry/

which means that we will need to be skilled in unit analysis and unit conversion if we want to use physics to analyze the human body. Let's practice again.

Everyday Example: Units for speed

Aasma ran as fast as she could while a friend drove alongside in a car with the speedometer reading 14 miles per hour (**MPH**). Can you determine how fast Aasma was running in units of meters per second (**m/s**)? There are 1.6 kilometers (**km**) in one mile (**mi**) and 1000 meters (**m**) in one kilometer. Remembering that there are 60 seconds (**s**) per minute (**min**) and 60 **min** per hour (**hr**).

$$14, \mathbf{MPH} = \left(\frac{14\,\mathbf{mi}}{1\,\mathbf{hr}}\right)\left(\frac{1.6\,\mathbf{km}}{1\,\mathbf{mi}}\right)\left(\frac{1000\,\mathbf{m}}{1\,\mathbf{km}}\right)\left(\frac{1\,\mathbf{hr}}{60\,\mathbf{min}}\right)\left(\frac{1\,\mathbf{min}}{60\,\mathbf{s}}\right)$$

$$= \left(\frac{6.2\,\mathbf{m}}{\mathbf{s}}\right) = 6.2\,meters\,per\,second$$

Reinforcement Exercises

An interactive or media element has been excluded from this version of the text. You can view it online here:
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CHAPTER 14.

HEART BEATS PER LIFETIME

ESTIMATING LIFETIME HEART BEATS

In addition to pb_glossary id=”3761″]unit analysis[/pb_glossary] with the chain-link method can also help us to answer difficult questions. For example, calculating how many heart beats an average person experiences during their lifetime seems daunting. With the chain-link method we can come up with an estimated value relatively quickly. A search of the internet finds that the average life expectancy in the U.S. is 78.8 years[1] and that the typical value for adult heart rate is between 60 **BPM** and 100 **BPM**[2] so let's take the middle-range value of 80 **BPM** and go from there.

Everyday Examples: Heart Beats Per Lifetime

We start with the average lifespan, which we will round to 80 years for simplicity:

$$80\,\mathbf{yr} = 80\,\cancel{\mathbf{yr}}\left(\frac{365\,\cancel{days}}{1\,\cancel{\mathbf{yr}}}\right)\left(\frac{24\,\cancel{\mathbf{hr}}}{1\,\cancel{days}}\right)\left(\frac{60\,\cancel{\mathbf{min}}}{1\,\cancel{\mathbf{hr}}}\right)\left(\frac{80\,\cancel{beats}}{1\,\cancel{\mathbf{min}}}\right) = 3,363,840,000\,beats$$

We have estimated that one lifetime will contain over three billion beats!

That's a big number! In fact, it's over three billion beats. As it turns out, humans are quite special among animals in the number of heartbeats per lifetime we experience. Visit the website of the beats per lifetime project[3] for more information and an interactive look at heart rate statistics for various species.

In the previous calculation we chose to use a heart rate of 80 **BPM**, which was an approximation rather than an actual measurement or calculation. Therefore, our answer is only an estimate. However, we don't expect anyone who lives to adulthood will get anywhere near 10x more or 10x fewer beats than this, so our answer is within an order of magnitude of what most people experience. Combining several already known, easily found, or approximate values to get a general idea of how big an answer should be, as we just did for beats per lifetime, provides an order of magnitude estimation. Play with this simulation to practice estimating sizes using only visual cues.

1. "Mortality Data" by National Vital Statistics System, Centers For Disease Control and Prevention
2. "Pulse" by Pubmed Health, U.S. National Library of Medicine
3. "The Heart Project" by The Heart Project, Rob Dunn Lab

ESTIMATION AND APPROXIMATION

Order of magnitude estimation often relies on approximate values, so *order of magnitude estimate* and approximation are often used interchangeably. Adding to confusion, approximation is often used interchangeably with assumption or uses approximation to describe a quick, rough measurement with a high degree of uncertainty. In order to maximize clarity this textbook will strive to stick to using terms as defined according to the following table.

Term	Definition	Everyday Example
Assumption	Ignoring some compilation of the in order to simplify the analysis or proceed even though information is lacking. Scientists state assumptions, justify why they were needed, and estimate their possible impact on results.	My cotton clothes are completely soaked through, so I assume they are not providing any insulating effect against the cold water.
Approximation Approximate	Act of coming up with a rough value using prior knowledge and assumptions, but not by making a measurement for the purpose of determining the value.	The water feels cold, but not shocking, similar to the 70 **°F** swimming lake, so the approximate water temperature is 70 **°F**.
Uncertainty (more about this later)	Amount by which a measured, calculated, or approximated value could be different from the actual value.	85 **°F** would feel comfortable like the 82 **°F** college pool and 55 **°F** feels very cold, so + 15 **F°** is my uncertainty from 70 **°F**.
Order of Magnitude Estimate	Result of combining assumptions, approximate values, and/or measurements with large uncertainty to calculate an answer with large uncertainty, but has the correct order of magnitude.	Using known data, I estimated my time to exhaustion or loss of consciousness to be 5 hours (less than 50 hours and more than 0.5 hours).

METRIC PREFIXES

Considering that our beats per lifetime answer is only an order of magnitude estimation, we should round our final answer to have fewer significant figures. Let's make it 3,000,000,000 beats per lifetime (**BPL**), or three billion **BPL**. A bit later in the chapter we will define what we mean by and significant figures and also talk more about why, when, and how we have to do this kind of rounding. For now, we notice that it's a bit distracting and a bit annoying writing out all those zeros, so by counting that there are nine places before the first digit we can use scientific notation and instead write: 3×10^9 **BPL**. Alternatively we can use a metric prefix. The prefix for 10^9 is Giga (**G**) so we can write: 3 ***GBPL*** (read as gigabeats per lifetime). The table below shows the common metric prefixes. For a much more comprehensive list of prefixes visit the NIST website. One advantage of using metric units is that the different size units are related directly by factors of ten. For example 1 meter = 100 **cm** rather than 1 foot = 12 inches.

Table of Metric Prefixes and Representative Physical Quantities [1]

prefix	symbol	value	example (some are approximate)			
exa	E	10^{18}	exameter	Em	10^{18} m	distance light travels in a century
peta	P	10^{15}	petasecond	Ps	10^{15} s	30 million years
tera	T	10^{12}	terawatt	TW	10^{12} W	powerful laser output
giga	G	10^{9}	gigahertz	GHz	10^{9} Hz	a microwave frequency
mega	M	10^{6}	megacurie	MCi	10^{6} Ci	high radioactivity
kilo	k	10^{3}	kilometer	km	10^{3} m	about 6/10 mile
hecto	h	10^{2}	hectoliter	hL	10^{2} L	26 gallons
deka	da	10^{1}	dekagram	dag	10^{1} g	teaspoon of butter
–	–	10^{0} =1	–	–	–	
deci	d	10^{-1}	deciliter	dL	10^{-1} L	less than half a soda

prefix	symbol	value	example (some are approximate)			
centi	c	10^{-2}	centimeter	cm	10^{-2} m	fingertip thickness
milli	m	10^{-3}	millimeter	mm	10^{-3} m	flea at its shoulders
micro	µ	10^{-6}	micrometer	µm	10^{-6} m	detail in microscope
nano	n	10^{-9}	nanogram	ng	10^{-9} g	small speck of dust
pico	p	10^{-12}	picofarad	pF	10^{-12} F	small capacitor in radio
femto	f	10^{-15}	femtometer	fm	10^{-15} m	size of a proton
atto	a	10^{-18}	attosecond	as	10^{-18} s	time light crosses an atom

Reinforcement Exercises

An interactive or media element has been excluded from this version of the text. You can view it online here:

https://openoregon.pressbooks.pub/bodyphysics/?p=199

CHAPTER 15.

HUMAN DIMENSIONS

HEIGHT (LENGTH)

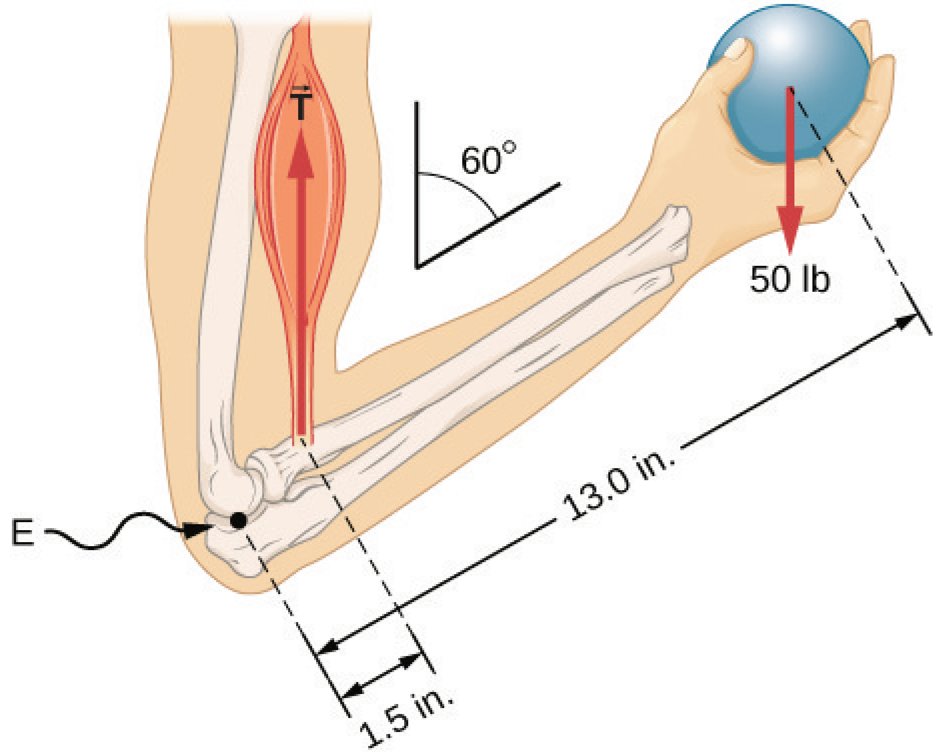
Height is a common body measurement typically measured in feet (**ft**) + inches (**in**) in the United States and centimeters (**cm**) elsewhere. These are length measurements, so the SI unit would be meters. Keep in mind that ***x*** feet + ***y*** inches is commonly denoted as ***x***' **y**".

> **Reinforcement Activity**
>
> Given that there are 2.54 **cm** in one inch, 12 **in** per one **ft**, and 100 **cm** in 1 **m**, use the chain link method to convert your height from the type of units you are familiar with into the other two types (**cm**, **m**, or **ft** + **in**).

RANGE OF MOTION

Range of motion is a common body measurement, especially while diagnosing injury or disease, tracking progress during physical therapy, or working to improve flexibility or form. Range of motion is often defined as an angle measured in *degrees* (°)through which a joint moves away from a reference position as seen in this video demonstration of how to use a goniometer for range of motion measurement.

For example, in the image below the joint angle is 60° and the reference position is a nearly horizontal forearm creating a 90° between the bicep muscle and the bones of the forearm. (This is not necessarily how the reference angle is defined for measuring elbow range of motion by health professionals)



The elbow joint flexed to form a 60° angle between the upper arm and forearm. Image Credit: Openstax University Physics

1

At times we might want to know how far something moves as it travels through an angle. For example, as the arm in the image below moved from 90° to 60° what distance did the hand and ball cover? In such cases, and many others, working with angles in radians (rads) can be helpful. We can convert between degrees and radians using the conversion factor:

(1) $2\pi, radians = 360,$

For example, in moving from 90° to the 60° seen in the previous diagram, the lower arm traversed 30° so we can convert this to radians:

$$30^{\circ} = 30\!/\left(\frac{2\pi\, radians}{360\!/}\right) = 0.523\, radians = 0.523\, \mathbf{rads}$$

The distance we are trying to calculate is known as the arc length, and to find it we multiply the angle in units of radians by the distance from the rotation point (also known as the radius). The symbols commonly used for arc length, angle and radius are: ℓ, θ, and Γ so in our example we will have:

$$\ell = thetar = (0.523\, \mathbf{rads})\,(13\, \mathbf{in}) = 6.8\, \mathbf{in}$$

We have found that the hand moves a distance of 6.8 inches when the forearm moves from horizontal to 60° of flexion. We have also discovered that **rads** are a placeholder unit, meaning that

1. OpenStax University Physics, University Physics Volume 1. OpenStax CNX. Jul 11, 2018 http://cnx.org/contents/d50f6e32-0fda-46ef-a362-9bd36ca7c97d@10.18

when **rads** gets multiplied by another unit, **rads** doesn't necessarily show up in the final units. Finally, we realize that we need to start keeping track of which symbols are most commonly used for which quantities. The following table shows the symbols most often used for some of the common quantities that we will encounter in this textbook. As we introduce new quantities going forward we will provide the common symbol in parenthesis when the quantity is first introduced.

Table of Common Physical Quantities and their Typical Symbols

Quantity	Most Commonly Used Symbol
Time	t
Length/ width/ distance/ height/ radius	l/w/d/h/r
Speed	v
Acceleration	a
Angle	θ
Area	A
Volume	V
Mass	m
Density	ρ
Force	F
Torque	tau
Work	W
Mechanical Energy/ Internal Energy/Heat	E/U/Q
Power	P
Momentum	rho
Temperature	T
Entropy	S

Reinforcement Activity

Measure the distance from your knee to your heel. How far does your heel actually move when the angle of your knee joint goes from 0° (straight leg) to 90°?

CHAPTER 16.

BODY SURFACE AREA

Surface area (A) is an important feature of the human body. Surface area affects the rate at which heat transfers into or out of the body and the rate at which certain chemicals can be absorbed through the skin. The severity of burn injuries depends on the degree of the burn, but also on the percentage of total body surface area affected[1]. The areas and surface areas of geometric shapes can be found using various formulas, such as $1/2 \times base \times height$ for triangles. The surface area of a convoluted shape such as the human body is difficult to measure, but we can use typical *ratios* (proportions) to quickly approximate body surface area. For example the palm surface area can be easily measured as $length \times width$ and the ratio of palm surface area to body surface area is typically 1/200, which might also be written as 1:200, 0.005, or 0.5%[2]. The units of area will be length units squared, such as square meters (meters squared or $\mathbf{m^2}$). We need to be careful when converting units involving powers (squared, cubed, etc.) and the chain-link method allows us to make sure our units cancel correctly.

Example square inches to square feet.

We are going to replace the carpet in a room. Carpet is sold by the square foot, so we are trying to determine the square footage of carpet in room. We use a measuring tape and find out that the room is 148 **in** long by 108 **in** wide. Multiplying length by width we get 15,984 $\mathbf{in^2}$. To convert to feet we need to multiply by the conversion factor *twice* in order to cancel the squared unit:

$$15,984\,\mathbf{in^2} = 15,984\,\cancel{in}\cdot\cancel{in}\left(\frac{1\,\mathbf{ft}}{12\,\cancel{in}}\right)\left(\frac{1\,\mathbf{ft}}{12\,\cancel{in}}\right)$$

Multiplying across the top and bottom we have:

$$15,984\,\mathbf{in^2} = 15,984\left(\frac{1\,\mathbf{ft^2}}{144}\right) = 111\,\mathbf{ft^2}$$

1. "Thermal Injuries" by Chemical Hazards Emergency Medical Management, U.S. Department of Health and Human Services
2. "The surface area of the hand and the palm for estimating percentage of total body surface area: results of a meta-analysis." by Rhodes J, Clay C, Phillips M., U.S. National Library of Medicine, U.S. Department of Health and Human Services

Reinforcement Activity

Measure your palm length and width in units of **cm**. Then calculate your palm surface area in units of **cm^2**. Next, calculate your approximate body surface area in units of **cm^2.** Finally use the chain-link method to convert your body surface area to both square inches (**in^2**) and **m^2**.

CHAPTER 17.

DOSAGE CALCULATIONS

Delivering medications is another critical function that Jolene performs many times on every shift and mistakes in dosage can have very serious consequences. Dosage calculations ensure patients receive the correct amount of each medication and Jolene uses the chain-link method of unit analysis to ensure that her patients receive correct dosages. "Three primary methods for calculation of medication dosages exist, and these include dimensional analysis, ratio proportion, and formula or desired-over-have method. Commonly used in solving chemistry and physics problems, dimensional analysis is fast becoming the go-to method for dosage calculations in nursing and the medical profession. Chances for error are diminished, thus increasing the popularity of these dosing calculations."[1]

Everyday Examples: Dosage Calculation

An MD orders 300 mg of Ibuprofen to be taken by a 6 kg infant every 4 hours. The label shows 75 – 150 mg/kg per day max. Is the physician's order within normal range?

First let's calculate the max dosage for this infant:

$$150\,\mathbf{mg/kg/day} = \left(150\,\frac{\mathbf{mg}}{\cancel{\mathbf{kg}}\,day}\right)(6\,\cancel{\mathbf{kg}}) = 900\,\frac{\mathbf{mg}}{day}$$

Now let's calculate the ordered dose.

$$300\,\mathbf{mg}/(4\,\mathbf{hrs}) = \left(300\,\frac{\mathbf{mg}}{4\,\cancel{\mathbf{hrs}}}\right)\left(\frac{24\,\cancel{\mathbf{hrs}}}{1\,day}\right) = 1800\,\frac{\mathbf{mg}}{day}$$

The dosage is not within the normal range.

[2]

1. "Dose Calculation" by Tammy J. Toney-Butler and Lance Wilcox, National Library of Medicine, National Institutes of Health
2. Adapted from "Medication Calculation Examination Study Guide " by Public Health Nursing, County of Los Angeles

Exercises

You want to give 50 **mg/kg** of Fortaz to a child who weighs 25.5 **kg**. Fortaz is available in an oral suspension labeled 100 **mg/mL**. How many **mL** should be administered?

CHAPTER 18.

UNIT 2 REVIEW

Key Terms and Concepts

Scientific Method/Process
Law
Principle
Theory
Empirical model
Physical (mechanistic) Model
SI measurement units
Unit conversion factor
Order of magnitude estimation
Scientific notation
Metric prefix

Unit 2 Learer Objectives [Corresponding Example Course Outcome #]

1. Describe the scientific method through an original example of how it could be applied to the student's everyday life. [5]
2. Identify the differences and relationships between empirical models, physical models, hypotheses, theories, and laws. [5]
3. Find necessary conversion factors and convert between SI and non-standard units for several physical quantities. [1]
4. Perform order of magnitude estimation. [2]

CHAPTER 19.

UNIT 2 PRACTICE AND ASSESSMENT

Outcome 1

1) What are the steps in the basic scientific method?

2) Use the summary of this 25-year, 7-country smoking and mortality study to identify the observation, question, hypothesis, test method, analysis method, reported uncertainty or confidence interval, and conclusions.

3) Explain how you could you apply the basic scientific method to a question from your everyday life. Be sure to identify how you would complete each step: observation, question, hypothesis, test method, analysis method, reported uncertainty or confidence interval, and conclusions.

4) How is the scientific method related to the modern scientific process?

Outcome 2

5) Provide an example of each of the following: empirical model, physical model, hypothesis, theory, and law. List any sources you used to find examples.

6) State which of the following categories the ideas listed below fall under: empirical model, physical or mechanistic model, hypothesis, theory, or law. List any sources you used to help you decide.

- Foreign organisms were thought to be present inside tumors (microscopic studies never found evidence of this).
- Due to genetic instability, successive mutations, appearing in cells, lead to selection of cancer cells which feature specific phenotypic traits[1].
- Natural Selection
- All living organisms consist of membrane encased cells
- Plate Tectonics
- Statistical relationships are found between measured forest fire smoke exposure and other available air quality data. Those relationships are used to predict forest fire smoke exposure in geographic areas where it's not easily measured[2].

1. "Evolving models of tumor origin and progression" by Iwona Mitrus, Ewa Bryndza, Aleksander Sochanik, and Stanisław Szala, U.S. National Library of Medicine, U.S. Department of Health and Human Services
2. "An empirical model to estimate daily forest fire smoke exposure over a large geographic area using air quality, meteorological, and remote sensing data" by Jiayun Yao and Sarah B Henderson, Journal of Exposure Science and Environmental Epidemiology, Nature Research

Outcome 3

7) What is the height in meters of a person who is 6 ft 1.0 **in**. tall? (Assume that 1 meter = 39.37 **in**.)

8) The speed of sound is measured to be 342 **m/s** on a certain day. What is this in km/h?

9) Soccer fields vary in size. A large soccer field is 115 **m** long and 85 **m** wide. What are its dimensions in feet + inches? (Assume that 1 meter equals 3.281 feet.)

10) Tectonic plates are large segments of the Earth's crust that move slowly. Suppose that one such plate has an average speed of 4.0 **cm**/year. (a) What distance does it move in 1 **s** at this speed? (b) What is its speed in kilometers per million years?

Outcome 4

11) Make an order of magnitude estimate of the number of cells in a hummingbird, assuming all the cells are the same size and approximating the the mass of an average cell to be ten times the mass of a bacterium. Be sure to cite your source for the size of a bacterium. (b) Making the same assumption, how many cells are there in a human?

(Exercises for outcomes 3 and 4 adapted from OpenStax College Physics [3]

3. OpenStax, College Physics. OpenStax CNX. Jul 16, 2018 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@11.35.

PART III.

UNIT 3: ERRORS IN BODY COMPOSITION MEASUREMENT

Learner Objectives

1. Compare and contrast precision, accuracy, systematic errors, and random errors. [4]
2. Identify sources of random and systematic errors.[4]
3. Explain how systematic and random errors affect precision, accuracy and uncertainty.[4]
4. Calculate and report uncertainties in measurements. [4]

CHAPTER 20.

BODY MASS INDEX

BODY COMPOSITION

Let's revisit Jolene, who works as a registered nurse (RN) on the medical/surgical (MED) floor of a large hospital. An important part of Jolene's job is patient education and on MED floor much of that education relates to healthy nutrition and body composition. Body composition attempts to quantify the relative amounts of different tissue types present in a person's body, typically with emphasis on ensuring a healthy amounts of fat relative to other tissues[1]. Body composition is just one of many measurable factors that health professionals use to evaluate a person's overall health and assess risk for type II diabetes, cardiovascular disease, sleep apnea, osteoarthritis, osteoporosis, and other medical conditions.

BODY MASS INDEX

The body mass index (BMI) attempts to categorize body composition using only height and weight as inputs. Health professionals like Jolene understand that the BMI can be useful when paired with other evaluations, but that it has many limitations when applied to individuals or very specific populations. For example, the extra weight caused by having more than average muscle can result in a false unhealthy weight categorization. [2]. Additional methods for determining body composition include bioelectric impedance, anthropometric, DEXA scan, hydrostatic weighing, and the skin fold method, which we will investigate in the following sections.[3]

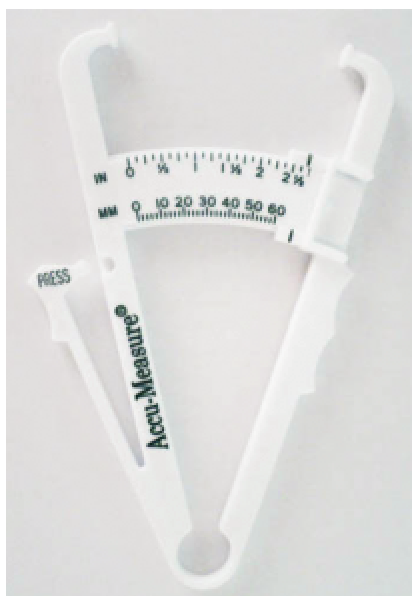
1. "Measuring body composition." by J C K Wells and M S Fewtrell, U.S. National Library of Medicine, U.S. Department of Health and Human Services
2. "Assessing your weight and health risk" by National Heart, Lung, and Blood Institute, U.S. Department of Health and Human Services
3. "The Math of Fitness" by Eric Kim, A Healthy U, Andrews University

CHAPTER 21.

THE SKINFOLD METHOD

THE SKINFOLD METHOD

The skinfold (caliper) method is one way to determine body composition. The skinfold method uses specially designed calipers to measure the thickness of skinfolds that are pinched from several specific locations on the body, as seen in this skinfold demonstration video[1].The skinfold thicknesses are correlated with body fat percentage using tables or equations that were produced by making both displacement and skinfold body composition measurements on many people[2].



Personal-use grade skinfold caliper used for measuring skinfold thickness for body fat percentage calculation. Image Credit: Jks via Wikimedia Commons

The skinfold method is quick, easy, and requires minimal equipment, however there are many possible ways for error to enter the measurement. Analyzing the skinfold method will help us

1. "3-Site Skinfold (Male)" by Sydney Richard, ptdirect
2. "Taking Skinfold Measurements" by ptdirect

understand the concepts of error, precision, accuracy, and uncertainty, which actually apply to all measurements. Watching the short skinfold demonstration video will help you follow the discussion of these concepts.

SKINFOLD MEASUREMENT ERROR

Let's say a physical therapist (PT) measures a particular skinfold thickness one time. The result might not be very accurate, or close to the actual value, for a variety of reasons. For example, measuring above or below the center of the skinfold would produce a measurement error that would affect the accuracy of the results.

The PT could then make many measurements of each skinfold. If the collection of measurements were all relatively close together then the measurement would have high precision. On the other hand if the measurements were all relatively far apart then the measurement would have low precision. The measurement precision can be affected by the measurement method and/or by the equipment so improving the method or the equipment can improve precision. For example, the PT might draw a mark on the skin to be sure the measurement is made in the same place every time. A caliper with larger dial will make it easier to see which mark is closest to the needle position.

Low precision is not desirable, but it doesn't have to ruin the measurement accuracy if the error causing the lack of precision is a random error. For example, if the PT happens to randomly measure at various distances above or below the actual skinfold center in equal amounts then this error is random. In this case averaging all of the measurements should give a result that is relatively close to the actual value. *The effect of a random error on the accuracy can be reduced by averaging more measurements.*

Systematic errors cannot be reduced by averaging because they bias the result away from the actual value in the same direction every time. For example, if the PT made a mark on the skin to improve precision, but the mark was actually in the wrong spot, then every measurement would be inaccurate in the same way. In this case averaging the results would not produce an accurate result. Instead, systematic errors must be reduced by improving methods or equipment. For example, using the displacement method instead of calipers would improve the accuracy of the body fat percentage measurement. These issues are part of why the caliper method is slowly going out of favor for determining body fat percentage. Another reason is that this specific method might embarrass and/or lower a patient's motivation to visit with their health care provider about their health, and that negative outcome is not worth the body fat percentage information that might be gained from the measurement (precision is typically not better than 3% body fat anyway[3]).

To summarize: *Systematic errors reduce accuracy and increase discrepancy while random errors reduce precision and increase measurement uncertainty. Random errors also affect accuracy, but the effect can be reduced by averaging more measurements.*

Exercises

A stadiometer (center photograph) is used to measure stature (natural height of a person standing upright).

3. "Body Composition" by J. Andrew Doyle, Exercise and Physical Fitness Page, Georgia State University Department of Kinesilogy and Health

A stadiometer is used to measure the stature of a person. The person stands against the rod which is marked in 1 cm increments (usually). A movable headpiece is placed to just touch the top of the head and the headpiece indicator line shows the stature on the rod. Image Credit: “Home_Banner” by Indian Health Service, U.S. Department of Health and Human Services

4

An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=291

4. "Height & Weight Measurement" by Indian Health Service, U.S. Department of Health and Human Services

CHAPTER 22.

PUPILLARY DISTANCE SELF-MEASUREMENT

You may have heard the old adage *"measure twice and cut once"*. Scientists take this concept to the extreme, so the saying would be more like: *"measure 50 times, then calculate the average and determine the possible uncertainty. Next cut a cheap piece of cardboard to the average size and test to make sure that it fits first, then finally cut the board. After you put the board in place, evaluate the goodness of fit, then think about how you could get an even better fit next time. Oh yeah, and write everything down along the way so you or anyone else can come along and follow the same process every time."* You might not make 50 measurements in your everyday life, but you can still use the concepts of error, precision, accuracy, and uncertainty to save yourself time, energy, and trouble.

Everyday Example

Tyler recently had an eye exam and his prescription changed. He has decided to order his new eyeglasses online to save money. He can upload a photo of his prescription, but he needs to provide his pupil distance, or PD and this is not written on the prescription. This is a common problem so the company website has a video explaining that PD is the distance between your pupils, measured in millimeters (**mm**) and showing how to measure PD using a ruler and a mirror.

Measuring pupil distance with a mirror. Image Credit: "Expert Reviewed How to Measure Your Interpupillary Distance" by WikiHow

[1]

Tyler tries the measurement and finds that the ruler is pretty far below his pupil and his pupil is several **mm** wide, so it's hard to line up the edge of the ruler with the center of one pupil and it's also hard to tell which mark on the ruler lines up best with the center of his other pupil. Even worse, his eye and the ruler both move a bit during the measurement. Tyler doesn't want to get his PD wrong and have to hassle with sending the glasses back.

Tyler makes several measurements and gets 56 **mm**, 57 **mm**, and 54 **mm** and he is uncertain of the actual value. He decides that because the marks on the ruler are plenty close together that piece of equipment isn't affecting his precision much. Instead, he decides his method is the culprit.

Tyler considers making a mark on his face just below one pupil that he can use to line up the edge of the ruler. After thinking more about it, Tyler realizes that if his mark wasn't perfect then this would introduce a systematic error into the measurement.

Instead, Tyler decides to ignore the precision issue and focus on getting an accurate result. He thinks it's likely that the difficulty in lining up the ruler makes his measurement sometimes too short and sometimes too long, so he decides to make a few more measurements and average all of the results. He makes four more measurements, getting 56 **mm**, 55 **mm**, 57 **mm** and 58 **mm**. Then he takes the average of all seven results:

$$Average\,PD = \frac{(56+57+54+56+55+57+58)\,\mathbf{mm}}{7} = 56.14\,\mathbf{mm}$$

The website for ordering glasses only let Tyler enter whole **mm** values, so he had to decide between 56 **mm** or 57 **mm**. Tyler's calculated average was closer to 56 **mm** so he entered that along with his prescription.

1. "Expert Reviewed How to Measure Your Interpupillary Distance" by WikiHow is licensed under CC BY-NC-SA 3.0

CHAPTER 23.

WORKING WITH UNCERTAINTIES

ERROR IN SCIENCE

The purpose of science is to discover new things, so we usually don't have an accepted answer to compare with the results of an experiment. Attempting to measure something that already has an accepted standard value before performing our experiment can expose systematic errors so that they can be fixed or taken into account. This is known as *calibration*. Evan after calibration we can't be certain that a systematic error has not affected our accuracy. "Students in science classes are in an artificial situation. Their experiments are necessarily repetitions of previous work, so the results are known. Because of this students learn a poor lesson about science. The good scientist [works hard to minimize possible sources of error and then] *assumes the experiment is not in error*. It is the only choice available. Later research, attempts by other scientists to repeat the result, will hopefully reveal any problems, but the first time around there is no such guide."[1] Bellevue College provides a more in-depth discussion of uncertainty and error.

UNCERTAINTY

Even assuming we have eliminated systematic errors from our measurement or experiment, the accuracy of our result could still be affected by random errors. Averaging many measurements reduces the effect of random error and analyzing the spread of those measurements allows us to define the measurement uncertainty. The *uncertainty of a measured value defines an interval that allows us to say with some defined level of confidence that a repetition of the measurement will produce a new result that lies within the interval.* Sometimes the uncertainty is determined primarily by the precision of an instrument, and sometimes other factors come into play.

Everyday Examples: Uncertainty in Tyler's Pupillary Distance Measurement

There are various statistical methods[2] to determine the uncertainty in Tyler's set of measurements, but we will just look at the range of values to get a quick idea of the precision in the measurement and use that for the uncertainty. We look at the seven values and the average and we notice that the values go up to 2 **mm** above the average and down to 2 **mm** below the average.

1. "Accuracy vs. Precision, and Error vs. Uncertainty" by Physics Resources and References, Bellevue College
2. "Uncertainty in Measurement Results" by NIST Reference on Constants Units and Uncertainty, National Institute of Standards and Technology

$$Average\ PD = \frac{(56+57+54+56+55+57+58)\ \mathbf{mm}}{7} = 56.14\,\mathbf{mm}$$

We will use 2 **mm** as a rough estimate of the uncertainty. This method is the known as the *half-range method* because it uses half of the difference between the maximum and minimum measured values as the uncertainty. If we wanted to show the final result of Tyler's measurements including uncertainty in the standard way then we would write:

$$PD = 56\,\mathbf{mm}\ \pm\ 2\,\mathbf{mm}$$

To complete our uncertainty statement we need to provide some kind of confidence. We could say that *most of the time a new measurement will be within 2* ***mm*** *of the average.*

With only seven values it will be difficult to further quantify the uncertainty. A common rule of thumb that can be cautiously applied when we have taken many measurements is that *about 70 % the time a new measurement will be less than 1/4 of the full range away from the average*. The full range in our example spans 4 **mm** so that would imply that roughly 70% of the time a new measurement will fall within 1 **mm** of the average. However, in our example we shouldn't really put a lot of weight into quoted percentage because have only seven measurements.

Examples: Rulers

What is the uncertainty in measuring the length of a piece of paper with a ruler?

The precision of a ruler typically determines the uncertainty in the measurement. If we have checked the length of the ruler against other standard rulers then we can assume it is accurate. A ruler with markings at a 1 **mm** interval will allow you to decide if the paper edge is closer to one mark or another. In other words, you will be able to tell if the paper edge is more or less than half-way between one mark and the next. We could then estimate the precision in the measurement to be half of one **mm** (0.5 **mm**) under ideal conditions because measurements would likely indicate the paper edge being closest to the same mark each time. To make a statement about our uncertainty we would then need a confidence level, in this case it would be qualitative: We *are very confident that repeated measurements will fall within 0.5* ***mm*** *above or below the average value.*

Getting a quantitative uncertainty typically requires statistical analysis of the measurement values. An example would be calculating the standard deviation and stating that *68 % of the time a repeated measurements will fall within one standard deviation from the mean).* Applying this type of statistical analysis requires making many repeated measurements and in this class we usually won't make enough so we need to just estimate our uncertainties.

Everyday Examples

What is the uncertainty in the mass measurement if you place a quarter on a standard electronic balance and obtain a reading of 6.72 **g**?

The scale is indicating the uncertainty in the measurement using the number of decimals it displays. The digits 6 and 7 are certain, and the 2 indicates that the mass of the quarter is likely between 6.71 and 6.73 grams. The quarter weighs *about* 6.72 grams, with a nominal uncertainty in the measurement of ± 0.01 gram. If the coin is weighed on a more sensitive balance, the mass might be 6.723 grams. This means its mass lies between 6.722 and 6.724 grams, an uncertainty of 0.001 gram. [3]

If wind currents in the room were causing the last digit to fluctuate between 6.77 grams and 5.67 grams then we would know the uncertainty was greater than the instrument precision. In that case we would have to average many values to ensure accuracy and then examine how those values were spread between 6.77 grams and 5.67 grams in order to determine the uncertainty.

Scientists try to reduce uncertainty as much as is practical and then use a variety of methods, some simple and some very sophisticated, to determine the size of the uncertainty for reported along with the results. In this textbook we will stick to the simple methods, but if you decide to continue studying science you will learn some of the more sophisticated methods[4][5].

Reinforcement Exercises

SIGNIFICANT FIGURES

Notice that in the previous example we have rounded the result to drop the decimal places from his result. This is because it would be meaningless to include decimals in the hundredth of a **mm** place if we don't even know the answer to within 2 **mm**, which is in the one **mm** place. Dropping the decimal places changes the number of significant figures in our result match our uncertainty. *The significant figures in a result are those digits that contribute to showing how precisely we know the result*.

Special consideration is given to zeros when counting significant figures. The zeros in 0.053 are not

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An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=354

3. "Measurement Uncertainty, Accuracy, and Precision" by Paul Flowers, Klaus Theopold, Richard Langley, William R. Robinson, PhD, Chemistry 2e, OpenStax is licensed under CC BY 4.0.
4. "Uncertainty in Measurement Results" by NIST Reference on Constants Units and Uncertainty, National Institute of Standards and Technology
5. "Experimental Uncertainty" by EngineerItProgram, California State University, Chio

significant, because they are only placeholders that locate the decimal point. There are two significant figures in 0.053. The zeros in 10.053 are not placeholders but are significant—this number has five significant figures. The zeros in 1300 may or may not be significant depending on the style of writing numbers. They could mean the number is known to the last digit, or they could be placeholders. So 1300 could have two, three, or four significant figures. Typically when you see a value like 1300 meters the zeros don't count, but we can avoid ambiguity by using scientific notation and writing 1.3×10^3 meters or using a metric prefix and writing 1.3 kilometers[6]. The table below will help you deal with zeros.

Significant Figure Examples

Result	Number of Placeholder Zeros	Number of Significant Figures
300.0	0	4
0.0003	4	1
0.000300	1 (first one)	6
300.07	0	5
300.0700	0	7
375	0	3
3,750,000	3 (typically)	3 (typically)
3.75×10^3	0	3

Reinforcement Activity

Determine how many significant figures are in each of these reported results:

- $517\,\mathbf{m}$
- $0.00180\,\mathbf{mi}$
- $6701\,\mathbf{s}$

Reinforcement Activity

Use the reported uncertainties to adjust each of the following results to the correct number of significant figures:

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https://openoregon.pressbooks.pub/bodyphysics/?p=354

6. OpenStax, College Physics. OpenStax CNX. Jul 6, 2018 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@11.20.

- $(517 \pm 20)\,\mathbf{m}$
- $(0.00180 \pm 0.001)\,\mathbf{mi}$
- $(6701 \pm 2)\,\mathbf{s}$

METHOD OF SIGNIFICANT FIGURES

Sometimes values are reported without uncertainty, but the level of uncertainty is still implied by the number of significant figures. When we express measured values, we can only list as many digits as we initially measured with our measuring tool. Tyler reported his first PD measurement as 56 mm, but he could not express this value as 56.31 mm because his measuring tool lacked the precision to measure down to the hundredth of a millimeter. Tyler had to decide which millimeter marking lined up with his pupil so the 1 mm digit hasuncertainty. The last digit in a measured value has always been estimated in some way by the person performing the measurement. Using the method of significant figures, *the last digit written down in a measurement is the first digit with some uncertainty.* [7] In this way significant figures indicate the precision of a measuring tool that was used to measure a value.

Whether uncertainties are written out or implied, we still need to account for the fact that measured values have uncertainty when we use those values in calculations. We will use four general rules to determine the number significant figures in our final answers.

- 1) For multiplication and division, the result should have the same number of significant figures as the least number of significant figures in any of the values being multiplied or divided.

- 2) For addition and subtraction, the result should have the same number of decimal places as the least number of decimals in any of the values being added or subtracted.

- 3) Counting discrete objects may have zero uncertainty. For example, sitting at a table with three oranges on it, you can measure the number of oranges on the table to be 3 with full certainty.

- 4) Definitions can have zero uncertainty. For example, the definition of a kilometer is 100 meters,

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7. OpenStax, College Physics. OpenStax CNX. Jul 6, 2018 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@11.20.

so if using this conversion factor in a calculation it does not contribute to adjusting your significant figures.

Everyday Examples

Each of Tyler's PD measurements are reported to the one's place due to his rulers' precision. He took the average to get the final result:

$$Average\ PD = \frac{(56+57+54+56+55+57+58)\,\mathbf{mm}}{7} = 56.14\,\mathbf{mm}$$

We see that to take the average Tyler had to add up the values:

$$(56+57+54+56+55+57+58)\,\mathbf{mm} = 393\,\mathbf{mm}$$

Applying the rule for addition (rule # 2), the result must have its last digit in the ones place because that was the least number of decimals in any number we used.

Tyler then divided by the number seven to get the average, but because this is just a count of how many measurements we made it has no uncertainty and doesn't affect the significant figures. So applying the rule for division, the final result should have the same number of significant figures as the least number in the division, which in this case is the three significant figures in 393 **mm**. Therefore our final result would be 56.1 **mm**, which implies that we certain of the 56, but we aren't sure about the 0.1 because have uncertainty in the tenth of a millimeter place. This result has more significant figures than were produced simply looking at the range of values to roughly estimate the uncertainty; but remember we expected that quick method to be an overestimate of uncertainty so this result makes sense.

Reinforcement Exercises

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CHAPTER 24.

OTHER METHODS OF REPORTING UNCERTAINTY*

Sometimes scientists report uncertainty as percentages of the result. For Tyler's example we would divide the uncertainty by the result and the multiply by 100 to find the percent uncertainty before writing it behind the result:

$$PD = 56\,\mathbf{mm} \pm \left(\frac{2\,\mathbf{mm}}{56\,\mathbf{mm}}\right) \times 100 = 56\,\mathbf{mm} \pm 4\%$$

Finding percent uncertainty is an important step in some of the more sophisticated methods of determining the total uncertainty in the result of a calculation that uses several numbers that each have uncertainties themselves. This text won't get into those sophisticated methods, but if you are curious you can read about some of them in Section 1.3 of OpenStax College Physics.

In addition to the methods we just discussed, Scientists sometimes report uncertainty in other ways, such as confidence intervals. Typically this method states 95% confidence that an actual value lies within the interval between two values. For example, this 25-year and 7-country study on cigarette smoking and mortality risk found that the hazard risk for all causes of death was 1.3x higher for smokers than non-smokers with a 95% confidence that the value was between 1.2x and 1.4x. (The risk was 1.8x higher for smokers of more than 10 cigarettes a day and even higher for death caused by coronary heart disease, all stroke, other arterial disease, lung cancer, other cancer, chronic obstructive pulmonary disease, and other disease in smokers[1].

1. "Cigarette smoking and mortality risk: twenty-five-year follow-up of the Seven Countries Study" by Jacobs DR Jr, Adachi H, Mulder I, Kromhout D, Menotti A, Nissinen A, Blackburn H., U.S. National Library of Medicine, U.S. Department of Heath and Human Services

CHAPTER 25.

UNIT 3 REVIEW

Key Takeaways

Measurement error

Random error

Systematic error

Precision

Accuracy

Uncertainty

Significant figures

Learner Objectives

1. Compare and contrast precision, accuracy, systematic errors, and random errors. [4]
2. Identify sources of random and systematic errors.[4]
3. Explain how systematic and random errors affect precision, accuracy and uncertainty.[4]
4. Calculate and report uncertainties in measurements. [4]

CHAPTER 26.

UNIT 3 PRACTICE AND ASSESSMENT

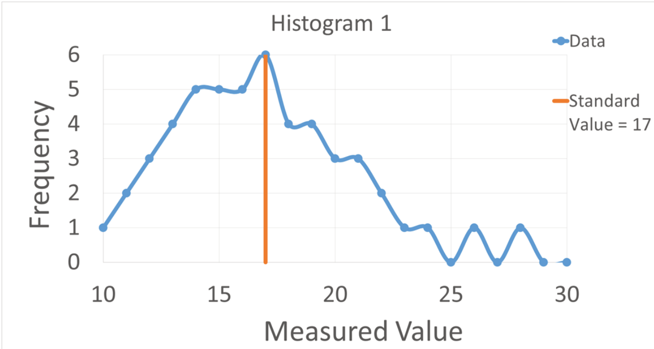
Outcomes 1, 2, 3

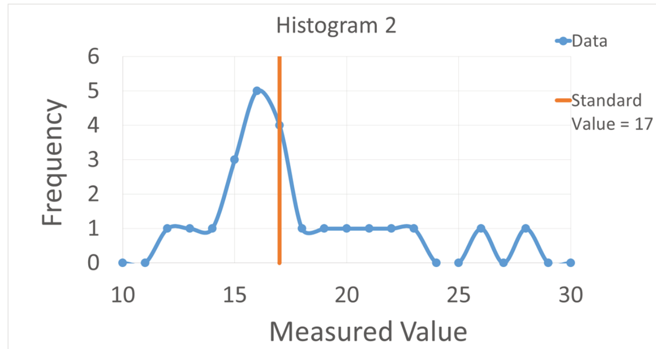
1. Would putting larger tires on a vehicle introduce random or systematic error into the speedometer reading? Would this affect the accuracy or precision (or both) of the speedometer? Explain your answers.

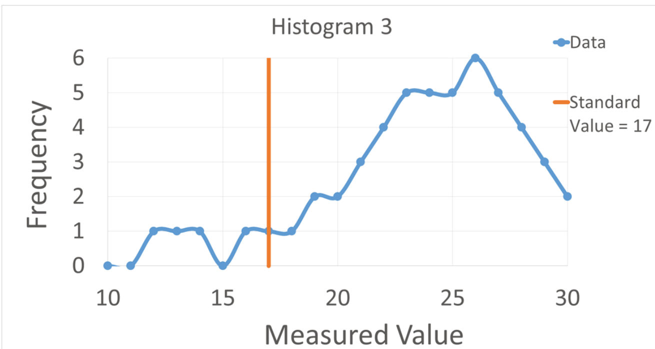
2. Would a wiggling baby introduce random or systematic error into a measurement of its weight? Would this affect the accuracy or precision (or both) of the weight measurement? Explain your answers.

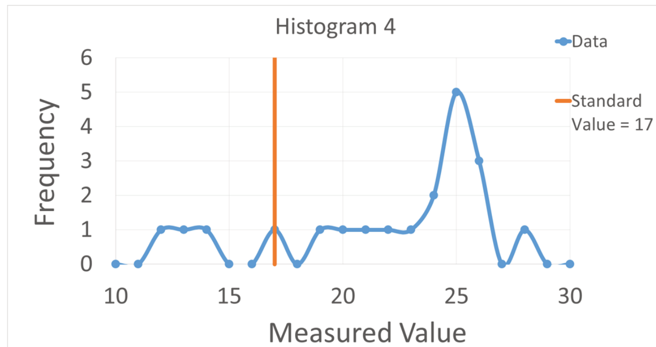
3. Would slightly under-filling measuring cups to prevent spilling ingredients introduce random or systematic error into the measurement of ingredient volumes? Would this affect the accuracy or precision (or both) of the measurement volumes. Explain your answers.

A set of measurements of a physical quantity was made for comparison to an accepted standard value. The data were plotted in graphs with the measured values on the horizontal axis and the number of times each value occurred on the vertical axis. This type of graph is known as a histogram and the data on the vertical axis are called the frequencies. Use the histograms below to answer the questions that follow.









Histograms of values measured during an experiment.

4. For each histogram state whether the data suggest the measurements were relatively accurate, precise, both, or neither. Explain your reasoning.
5. For each histogram state what types of errors were likely to be relatively significant: random, systematic, both or neither. Explain your reasoning.

Outcome 4

6)A person measures his or her heart rate by counting the number of beats in 30 **s** as timed using a clock on the wall, such as the one in the image below. They start counting when the second hand jumps onto a particular tick mark (say the 12) and then stop counting when it jumps to the opposite mark (say the 6). A reasonable estimate of the uncertainty in the time measurement would be which of the values listed below? Explain your reasoning.

a) 0.05 **s**
b) 0.5 **s**
c) 5 **s**
d) 50 **s**

Typical wall clock with hour, minute, second hands and 1 hour, 1 min (1s) divisions. Image Credit: Clock by Lee Haywood via Wikimedia Commons

[1]

7. Estimate the uncertainty in counting the beats in the previous problem. Explain your reasoning.

*8) If 47 beats were counted by the person in the previous problem, what a was their heart rate in BPM in correct significant figures. Indicate the total % uncertainty and total uncertainty.

1. Clock By Lee Haywood from Wollaton, Nottingham, England (Clock) [CC BY-SA 2.0 (https://creativecommons.org/licenses/by-sa/2.0)], via Wikimedia Commons

PART IV.

UNIT 4: BETTER BODY COMPOSITION MEASUREMENT

Learner Objectives

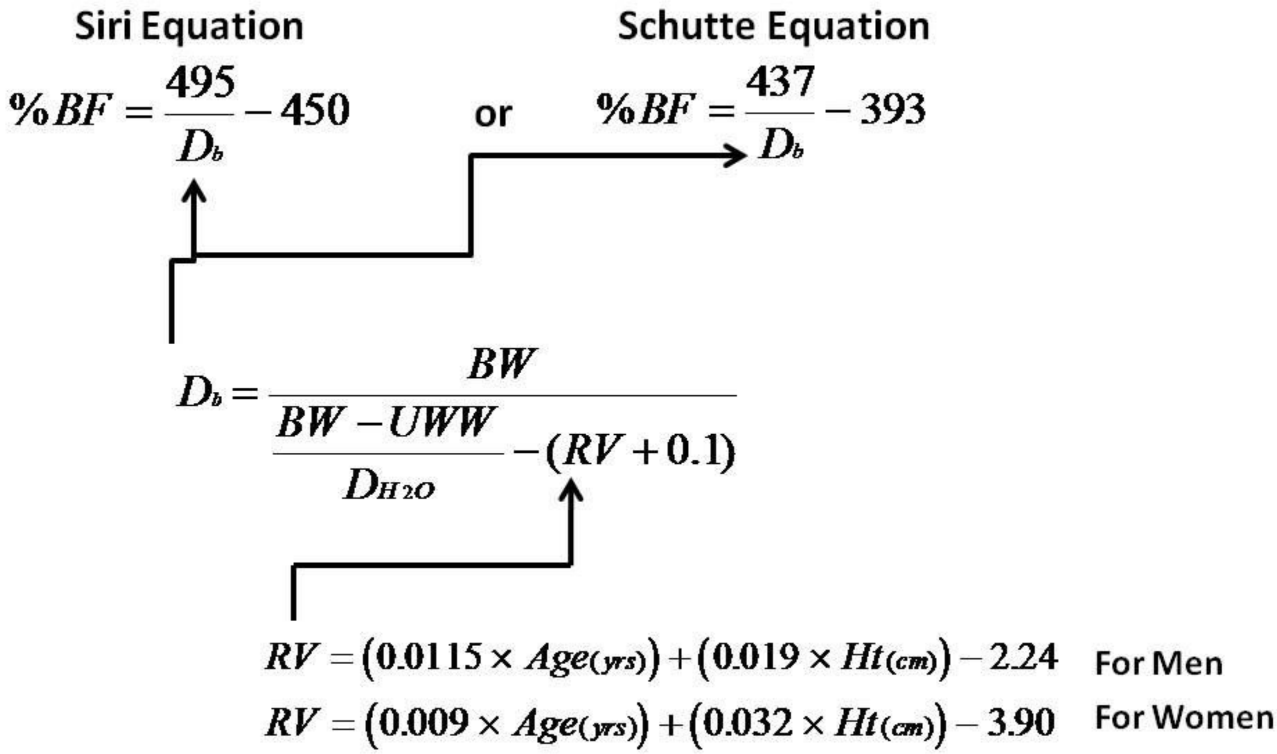
1. Compare and contrast: mass, volume, density, weight and apparent weight and explain how each are measured.[2]
2. Apply the concept of static equilibrium to determine the magnitude and direction of unknown forces.[3]
3. Apply Archimedes' principle and density concepts to predict if objects will sink or float.[2]
4. Determine density by hydrostatic weighing and from mass and volume measurements.[4]

CHAPTER 27.

BODY DENSITY

BODY FAT PERCENTAGE FROM BODY DENSITY

Health care professionals like our RN friend Jolene understand that BMI provides a relatively quick way to asses body composition and gives providers and patients an easy method for monitoring changes, but it does not always accurately capture a person's body composition. The errors common to the previously discussed skinfold method and the BMI can be somewhat avoided by actually measuring body density, which can then be used in empirical formulas that interpolate body fat percentage from body density:



Formulas used in calculating residual lung volume, body density, and body fat percentage. Image Credit: Measure Body Fat Via Under Water Weighing by MattVerlinich via Instructables

[1]

Your lab for this unit might involve some of these formulas and if you are curious you can read more about those formulas, play with a simulation of hydrostatic weighing, check out a website that does the calculations for you, and see that different formulas have been developed for different population sets in an effort to increase accuracy.[2]. Determining body fat percentage from body density is not something that Jolene would do on the MED floor, but athletic training facilities and clinics specializing in care associated with body composition might use this method.

BODY DENSITY

MASS AND VOLUME

In order to understand density and how it might be measured, we need to know that volume (V) is the amount of space taken up by an object. Mass (m) is a measure how strongly an object attracts other objects by gravitation and resists changes in its motion. Atoms are the matter that make up everyday

1. "Measure Body Fat via Under Water Weighing" by Matt Verlinich, Instructables, Autodesk
2. "Under Water Weighing" by University of Vermont College of Medicine, Department of Nutrition and Food Science,

objects like the body, and each type of atom exhibits a certain mass, so we sometimes speak of the mass as a measure of the amount of matter in the object. For example, 6.022×10^{23} carbon atoms will exhibit a mass of 12.011 grams. The number at the bottom of each square in the periodic table tells you the mass (in grams) exhibited by 6.022×10^{23} of that type of atom. This seemingly odd number is known as *Avogadro's Number*.

DENSITY

The SI units for volume and mass are cubic meters (**m**^{3}) and kilograms (**kg**). Mass Density (ϱ), which we usually shorten to just density, for any object is defined as its mass divided by its volume. The same mass of different materials will have different volume, and thus different densities. For example 1 **kg** of foam takes up much more space than 1 **kg** of steel (in fact, about 80 times more). This giant table of material densities is a useful reference (click the ***kg/m^3*** *button* to see the values in SI units).

Reinforcement Exercises

Sometimes weight density is used instead of mass density, in which case weight (pull of gravity on an object) rather than mass is divided by the object volume. The following chapters will explain how we measure the volume, weight, and mass of a body in order to calculate body density for use in determining body composition.

Reinforcement Exercises

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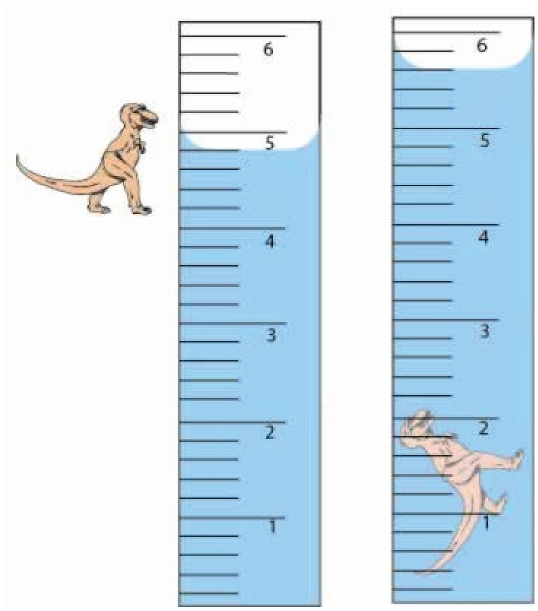
CHAPTER 28.

BODY VOLUME BY DISPLACEMENT

VOLUME BY DISPLACEMENT

The displacement method (submersion, or dunking method) can be used to accurately measure the volume of the human body and other oddly shaped objects by measuring the volume of fluid displaced when the object is submerged, as illustrated in the figure below.



When the dinosaur is submerged some of the water is displaced and the water level rises. The displaced volume is measured by reading the gradings, in this case 49 to 53, for a total of 4 volume units (which could be ***cm***^{3} *for a toy dinosaur or* ***m***^{3} *for a real one). Image credit: Greg Golz, Exploring Science*

1

1. "Density Using Displacement" by Greg Golz, https://sites.google.com/site/sciencegolz/ is licensed under CC BY 4.0

BODY VOLUME

Measuring body volume with the displacement method requires specialized equipment, such as a large tub of water with volume grading (markings) or a special scale that can measure the apparent weight of a submerged person. Recently technologies have been developed that allow for air rather than water to be used as the submersion fluid, opening up the method to a broader set of the population [2]

"Infant body composition through air displacement plethysmography" by Cosmed via Wikimedia Commons

3

2. "Bod Pod Services" by Oregon Clinical & Translational Research Institute, Oregon Health Sciences University.
3. By Cosmed [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], from Wikimedia Commons

CHAPTER 29.

BODY WEIGHT

WEIGHT AS A FORCE

Now that we know how to find the volume of a body, we just need to measure body mass in order to find body density. We typically measure the mass of a body by first measuring the weight using a scale, and then calculating mass from the measured weight. Weight is just another name for the force of gravity on an object. In everyday experience, a force (F) is any push or pull on an object. Forces can move objects, deform objects, or both. Often W is used to abbreviate weight, but F_g is also used because it reminds us that an object's weight and the force of gravity on the object are the same thing. Throughout this book we will learn about other forces, including buoyant force, tension, normal force, friction, and air resistance. We typically represent forces with arrows that point in the direction the force pushes (or pulls). We usually try to make the length of the arrows proportional to how big the forces are, in which case the arrows can be called vectors. The SI unit for weight, and all other forces, is the Newton(**N**). In the U.S. we often use pounds (**lbs**) instead of Newtons as our unit of force. One pound is equal to 4.45 Newtons.

Reinforcement Exercises

Reinforcement Activity: Free Body Diagrams

Draw a stick figure of a person jumping on a trampoline. Then add an arrow representing gravity acting on you while they

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are in the air. The arrow should start at the center of the person and point in the direction that gravity acting. Label the force arrow.

Draw a second figure that is just standing on the trampoline and add arrows to represent the forces acting on the person. Label the forces. [Hint: There are two forces.]

Do you think the lengths of the two force vectors should be the same or different? Explain your thought process.

FREE BODY DIAGRAMS

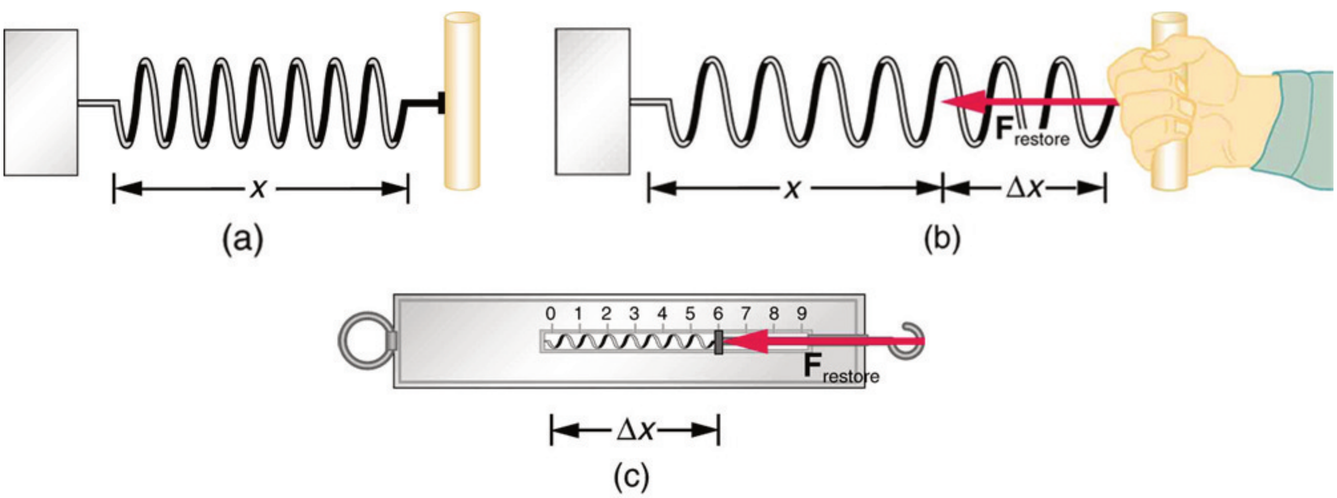
A diagram, such as you have drawn above, that represents an object in a simplified way and shows the forces acting on it using vectors is known as a free body diagram. We often make the diagrams very simple and represent the object with just a dot, so that the force vectors are easier to see.

CHAPTER 30.

MEASURING BODY WEIGHT

SPRINGS

The predictable and repeatable way in which springs stretch in response to applied forces provides a method for measuring weight and other forces. Furthermore, springs can be designed to produce conveniently measurable stretch distances for a wide variety of forces. For example, if you were pull on each end of a steel wire that had the same diameter as a human hair, you would not be able to noticeably stretch the wire. However, if that rod were formed into a spring, then you could stretch the spring with your bare hands.



The force exerted on a stretched spring determines how far it stretches. (a) This spring has a length x when not stretched. (b) The resistance of the spring to deformation causes a force, $F_{restore}$ to be exerted back on whatever is pulling on the hook. (c) A spring scale is one device that uses a spring to measure force. Image Credit: OpenStax University Physics

1

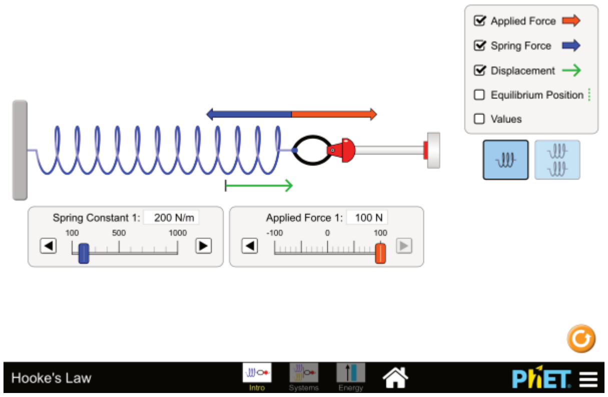
Springs follow Hooke's Law which states that the restoring force, F_R exerted by the spring is equal to the stretch or compression distance, known as the displacement (Δx), multiplied by spring stiffness (k) and the direction of the force is opposite to the direction of the displacement.

(1) $\mathbf{F_R} = -k\mathbf{\Delta x}$

1. OpenStax University Physics, University Physics Volume 1. OpenStax CNX. Sep 14, 2018 http://cnx.org/contents/d50f6e32-0fda-46ef-a362-9bd36ca7c97d@11.28.

A higher spring stiffness means the spring shows a greater resistance to stretching or compressing. Spring stiffness is often called the spring constant. The negative sign tells us that the restoring force provided by the spring always points in the opposite direction as the displacement.

Check out this simulation of Hooke's Law:



Reinforcement Activity

VECTORS

As we analyze forces we are beginning to see that it's very important to keep track of their directions in order to know if they are cancelling out or adding together, which is why we represent them with vectors. As we move through the textbook we will encounter a few other quantities that are also vectors and we will need to remember which quantities require keeping track of their direction (vectors) and which don't (scalars). For example, the displacement of the spring is vector because is has a size that tells us how far it was displaced, and a direction that tells whether it was stretched or compressed that distance. We will make the symbols for vectors **bold** when writing equations. We should be able to avoid confusion with our **bold** units by only writing units behind numeric values and not behind symbols. You may have noticed that already started using this **bold** convention in the equation for the spring above. In some cases we might only be interested the size of a vector, called the magnitude, and then we will not make it bold.

WEIGHT WITH A SPRING SCALE

Spring scales are designed to take advantage of Hooke's law to determine the size of the force stretching the spring by measuring the displacement. For example when hanging the object from the

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spring scale the force of gravity will pull it down and the restoring force in the spring pulls it up, as represented by the free body diagram of the turtle in the following image:

Biologist Dr. Paula Khan holds still and keeps the scale vertical while she weighs a desert tortoise before release as part of the Fort Irwin, Calif., tortoise translocation. Photo Credit: "Paula Khan" by Neal Snyder via Wikimedia Commons

2

When weighing an object that is not in motion we know the restoring force from the spring must perfectly balance the weight because the object remains still, which is a state known as static equilibrium. In fact, *anytime an object is at rest (a.k.a static) then all of the forces on the object must be perfectly balanced out, (a.k.a equilibrium)*. Therefore, if we are careful to make sure the object remains still we can measure the weight by finding the restoring force from the spring, which is determined by the displacement. Typically spring scales will have markings on them which indicate the restoring force for each stretch distance, so we don't have to actually calculate the restoring force from the displacement every time we use the scale.

Many analog scales are based on multiple springs or the resistance to deformation by objects other than springs, but they still determine weight using measurement of a deformation combined with a known relation between deformation and force and an assumption of static equilibrium.

2. "Paula Khan" by Neal Snyder via Wikimedia Commons released in the public domain by U.S. Army Environmental Command

Reinforcement Exercises

DIGITAL SCALES

Many modern scales follow the same principle as spring scales, but instead of measuring the deformation directly, they measure an electric voltage created by a material in response to being deformed. Materials that produce voltages in response to deformation are known as piezoelectrics. As long as the relations between voltage and deformation and between deformation and applied force are both known, the scale can determine your weight by measuring a voltage.

An interesting aspect of the piezoelectric effect is reversibility, meaning that piezoelectric materials not only produce a voltage in response to deformation, they will also deform in response to an applied voltage, which allows for piezoelectric motors.

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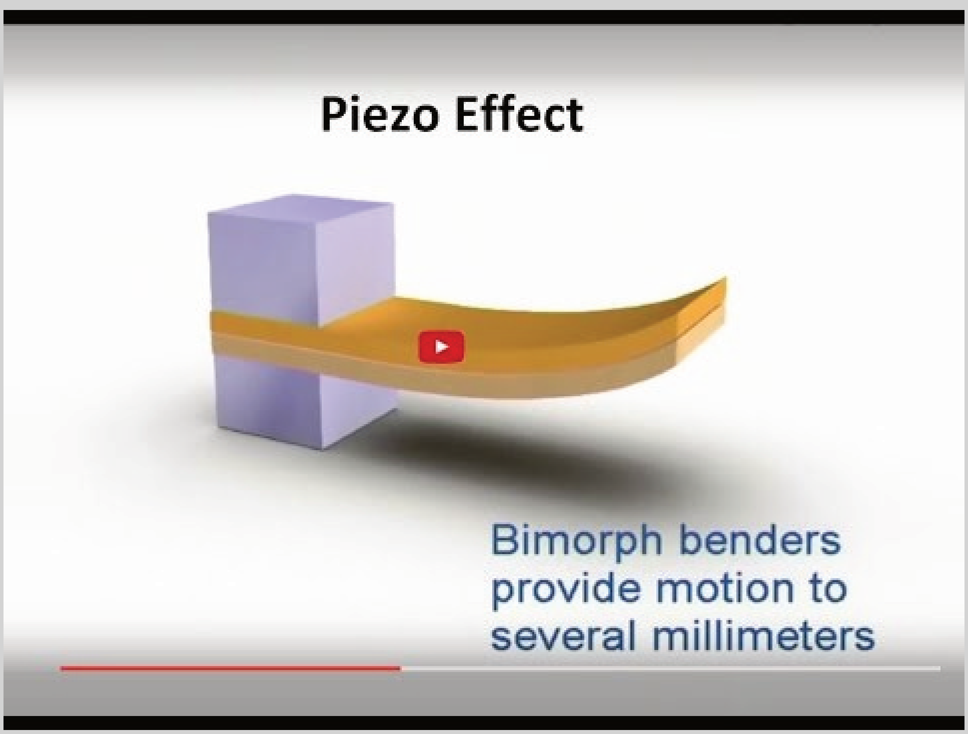

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CHAPTER 31.

BODY DENSITY FROM DISPLACEMENT AND WEIGHT

MASS FROM WEIGHT

Scales measure weight, but to calculate body density we need mass. Some scales read off mass, such as the electronic scale in the image below, even though they actually measure weight as discussed in the previous chapter.

A food product sits on a digital weighing scale with options for displaying weight in pounds or mass in kilograms or grams. The readout is 243 g. Image Credit: "Digi-keukenweegschaal1284" by Algont via wikimedia commons.

[1]

Mass can be determined from a weight because weight is just the force of gravity on the body and force of gravity depends on mass in a known way. On the surface of the Earth, the force gravity on an object is related to its mass by the equation:

(1) $Force\,of\,gravity = mass\,\times\,acceleration\,due\,to\,gravity$)

The acceleration due to gravity on Earth, typically abbreviated to g, has a value of $9.8\ \mathbf{m/s^2}$ and doesn't change much over the entire surface of the Earth. Therefore we (and scales) can measure weight and then use equation (1) above to calculate mass. Understanding why the constant g is called the *acceleration due to gravity* requires introducing acceleration, which we will do in a later unit, so for now we recognize it as a constant value that relates mass and weight for objects on the surface of Earth.

1. "Digi-keukenweegschaal1284" by Algont [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0/)] via wikimedia commons.

Force is a vector, so we need to specify a direction for the gravitational force, which is always down toward Earth's center. We can summarize the previous equation in symbol form:

(2) $\mathbf{F} = mg \quad (downward)$

Reinforcement Exercises: Helen Maroulis

You can read more about Helen Maroulis here

CALCULATING BODY DENSITY

We now know how to measure volume by displacement and how to determine mass from a weight measurement so we should be able to determine body density. First we measure the weight, then calculate the mass. Dividing the mass by the volume found from our displacement measurement will give us the body density. Give it a try:

Reinforcement Exercises: Body Density

BODY WEIGHT AND MASS ON THE MOON

The value of *g* only holds constant near the surface of the Earth, and therefore scales that use equation (1) to calculate mass from measured weight will read incorrect results. For example, your mass doesn't change just because you go to the moon (there isn't suddenly less matter inside you), but your weight does change. In fact if you stood on a scale on the moon it would measure a weight about 1/6 of what it would read on Earth. The scale wouldn't know you were on the moon instead of the Earth, so if the scale then tried to calculate your mass from weight, it would read a mass that is 1/6 the actual value. Of course you didn't lose 5/6 of yourself on the way there, so that would not be correct.

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UNIVERSAL LAW OF GRAVITATION*

When you do want to calculate the force of gravity and you are not near the surface of the Earth then use the Universal Law of Gravitation.

The Universal Law of Gravitation states that the gravitational force between two objects depends on the mass of each object (m_1 and m_2) and the distance between their centers, (r). To calculate the gravitational force we need to multiply the two masses together, divide by the distance between them squared, and finally multiply by the universal gravitational constant G, which always has the same value of $6.67408 \times 10^{-11} \frac{\mathbf{m^3}}{\mathbf{kg^1 s^2}}$. Written in equation form the universal law of gravitation is:

(3) $\mathrm{F}_g = G\frac{m_1 m_2}{r^2}$

Reinforcement Exercise

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CHAPTER 32.

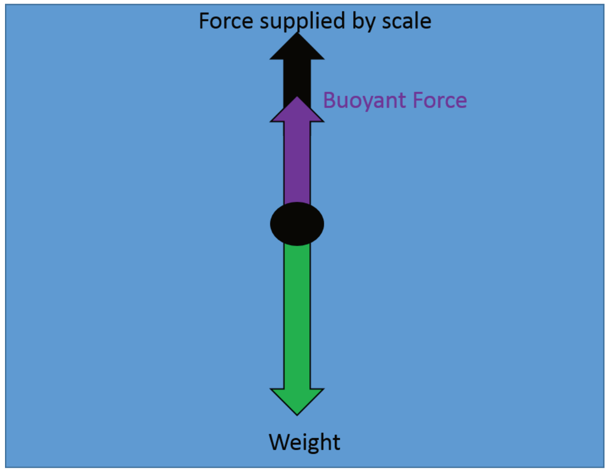
UNDER WATER WEIGHT

APPARENT WEIGHT

When an object is held still under water it *appears* to weigh less than it does in air because the buoyant force is helping to hold it up (balance its weight). For this reason, the reduced force you need to apply to hold the object is known as the apparent weight. When a scale is used to weigh an object submerged in water the scale will read the apparent weight. When performing hydrostatic weighing for body composition measurement the apparent weight is often called the under water weight (UWW).

STATIC EQUILIBRIUM

When weighing under water we know the buoyant force must be equal to the difference between the weight and apparent weight because the object remains still, which is a state known as static equilibrium. For an object to be in static equilibrium, all of the forces on it must be balanced so that there is no net force. For the case of under water weighing, the buoyant force plus the force provided by the scale must perfectly balance the weight of the object, as long as the object is holding still. We can use arrows to represent the forces on an object and visualize how they are balanced or unbalanced. This type of diagram is known as a free body diagram (FBD). The direction of arrows shows the direction of the forces and the arrow lengths shows the size (magnitude) of the force. In this case we call the arrows vectors and say the forces they represent are vector quantities. The FBD for a person undergoing hydrostatic weighing would look like this:



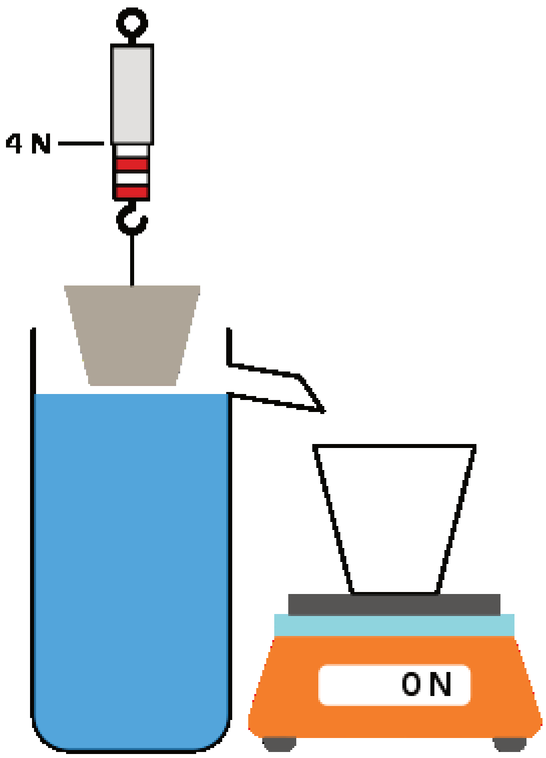
Free body diagram of an object hanging from a scale, submerged in water. The length of the weight arrow is equal to the combined lengths of the force supplied by the scale and the buoyant force. A scale will read the weight that it must supply, therefore it will read an apparent weight for submerged objects that is less than the actual weight.

We learned in the last chapter that scales measure the force that they are supplying to other objects. The scale must supply less restoring force to counteract weight and maintain static equilibrium when the buoyant force is also helping, therefore the scale will provide a apparent weight reading that is less than the actual weight.

ARCHIMEDES' PRINCIPLE

Measuring the weight and apparent weight of a body allows us to calculate its density because the buoyant force that causes the reduction in apparent weight has a special relation to the amount of water being displaced by the body. Archimedes' Principle states that *the buoyant force provided by a fluid is equal to the weight of the fluid displaced*.

Reinforcement Exercises



Demonstration of Archimedes' Principle. The buoyant force is equal to the weight of the water displaced, which in this case is 3 **N***. The buoyant force cancels out 3* **N** *worth of the objects weight, so the scale only pulls up with 1* **N** *to hold the object in static equilibrium. As a result, the scale reads an apparent weight of only 1* **N***. Image Credit: "Archimedes-principle" by MikeRun via Wikimedia Commons*

1

BUOYANT FORCE AND DENSITY

A given mass of low density tissue will take up volume relative to the same mass of high density tissue. Taking up the volume means more water is displaced when the body is submerged so the

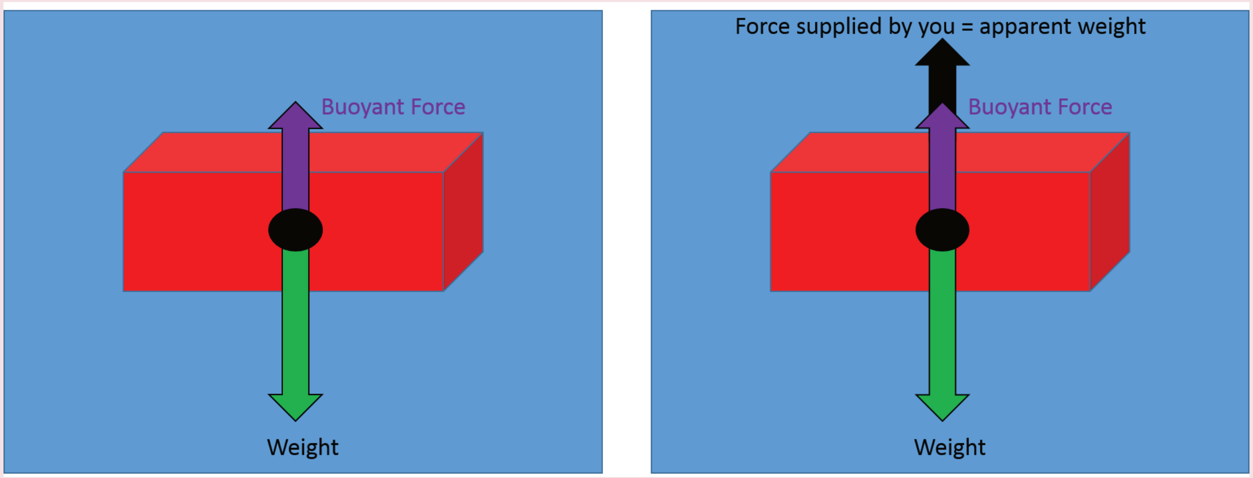
An interactive or media element has been excluded from this version of the text. You can view it online here:
https://openoregon.pressbooks.pub/bodyphysics/?p=1497

1. "Archimedes-principle"By MikeRun [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], from Wikimedia Commons

buoyant force will be larger compared to the weight than it would be for a more dense body. In turn, that means that apparent weight is smaller relative to actual weight for bodies of higher density. By comparing weight and apparent weight, the body density can be determined. We will do that in the next chapter, but first we should become more familiar with the Buoyant force.

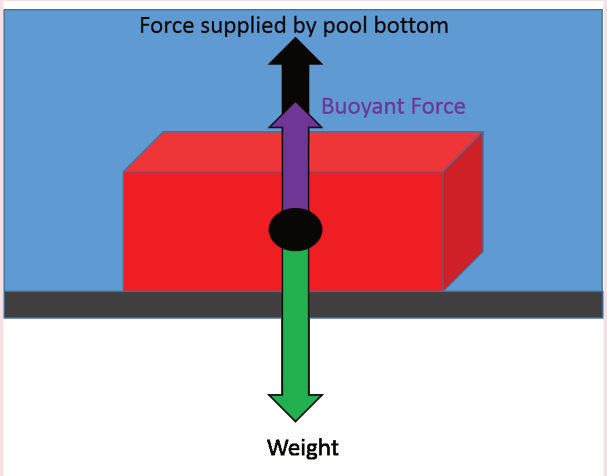
Everyday Example

The water displaced by a brick weighs less than the brick so the buoyant force cannot cancel out the weight of the brick and it will tend to sink (left diagram). To hold the brick in place you must provide the remaining upward force to balance the weight and maintain static equilibrium. That force is less than the weight in air so the brick *appears* to weigh less in the water (right diagram).



Free body diagrams for bricks in water. The brick on the left is sinking, the brick on the right is being held in place by you.

If you let go of the brick it will be out of equilibrium and sink to the pool bottom. At that point the pool bottom is providing the extra upward force to balance out the weight, and the brick is once again in static equilibrium.

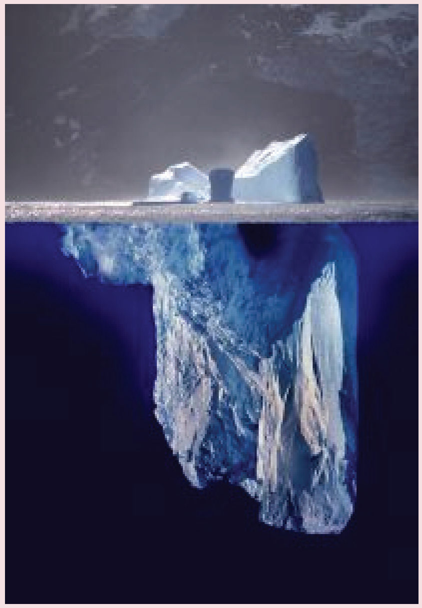


Free body diagram of a brick sitting on the bottom of a pool.

The water displaced by an entire beach ball weighs more than a beach ball, so if you hold one under water the buoyant force will be greater than the weight. Your hand is providing the extra downward force to balance out the forces and maintain static equilibrium (left diagram). When you let go, the forces will be unbalanced and the ball will begin moving upward (right diagram).

Free body diagrams of a beach ball under water. The ball on the left is held in place by you. The ball on the right will float upwards.

The density of ice is only about 9/10 that of water. The weight of the water displaced by only 9/10 of the iceberg has the same weight as the entire iceberg. Therefore, 1/10 of the iceberg must remain exposed in order for the weight and buoyant forces to be balanced and the iceberg to be in static equilibrium.



An iceberg floating with roughly 9/10 of its volume submerged. Image Credit: "Iceberg" created by Uwe Kils (iceberg) and User:Wiska Bodo (sky) via Wikimedia Commons

2

Reinforcement Exercises

Check out this buoyancy simulation which lets you control how much objects of different masses are submerged and shows you the resulting buoyant force along with forces provided by you and a scale at the bottom of the pool (apparent weight).

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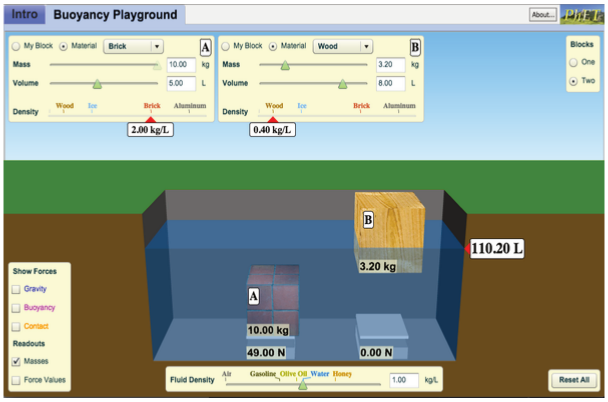
2. "Iceberg" created by Uwe Kils (iceberg) and User:Wiska Bodo (sky). [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons



Not-So-Everyday Example

Submarines control how much water they displace by pumping water in and out of tanks within the submarine. When water is pumped inside, then that water is not displaced by the sub and it doesn't count toward increasing the buoyant force. Conversely, when water is pumped out that water is now displaced by the sub and the buoyant force increases, which is the concept behind the maneuver in the following video:

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CHAPTER 33.

HYDROSTATIC WEIGHING

The method of hydrostatic weighing allows us to determine the average density (ρ) of a any object without any need for a volume (V) measurement by measuring only its weight (W_0) and apparent weight, also known as under water weight (UWW). To see how we arrive at this useful result, follow the steps in the derivation at the end of this chapter.

(1) $$\rho = \frac{W_O}{W_O - F_A}\rho_W$$

Reinforcement Exercises

The previous equation is very similar to the body density equation used for hydrostatic weighing, but you will notice a slight difference. The previous equation determines the average density of the object including any hollow parts containing trapped air, but the body density equation is designed to determine the average density of body tissues only, not including trapped air. Therefore, the body density equation is modified to account for a volume of air trapped inside the body, known as the residual volume (RV). Also different standard symbols are used to designate body density, apparent weight, and water density.

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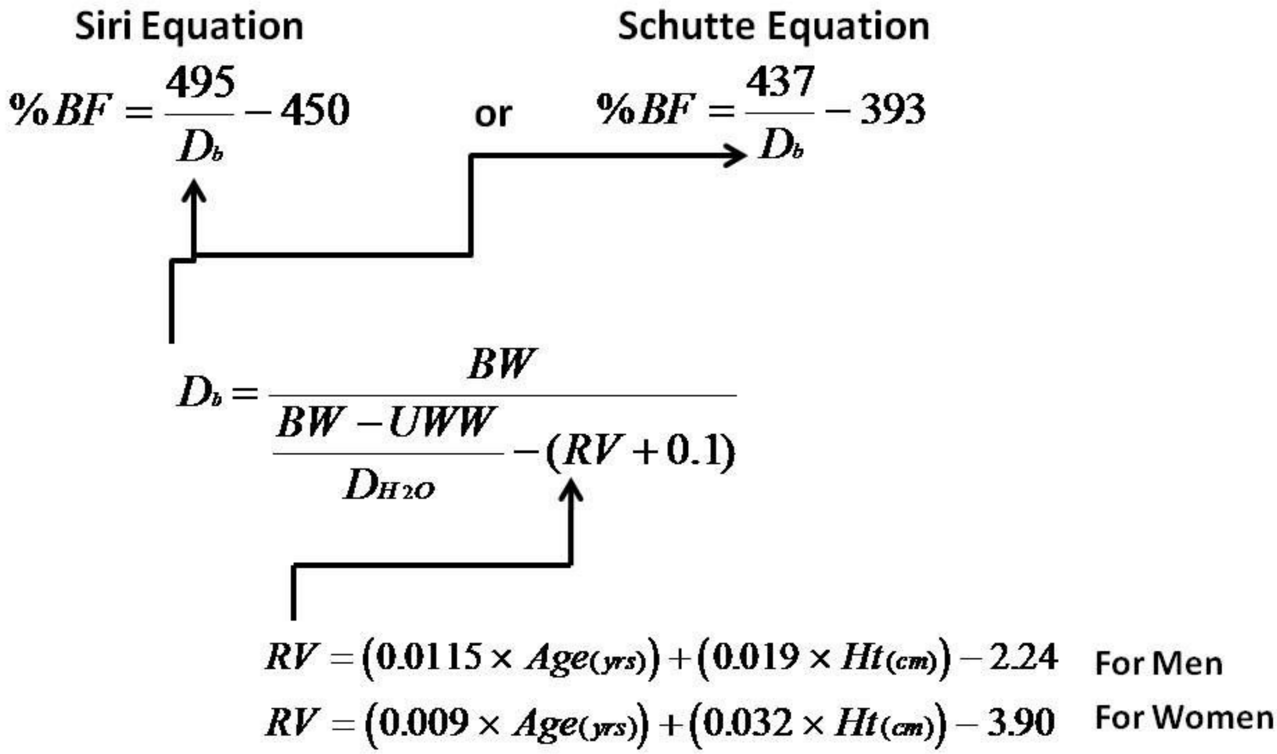

Formulas used in calculating residual lung volume, body density, and body fat percentage. Image Credit: Measure Body Fat Via Under Water Weighing by MattVerlinich via Instructables

[1]

SPECIFIC GRAVITY

The ratio of the density of a substance to that of water is known as the specific gravity. Specific gravity can be determined by hydrostatic weighing. If we simply divide both sides of our density equation by the density of water we will have a formula for the specific gravity with weight and apparent weight as input:

$$SG = \frac{\rho}{\rho_W} = \frac{W_O}{W_O - F_A} \quad (2)$$

1. "Measure Body Fat via Under Water Weighing" by Matt Verlinich, Instructables, Autodesk

Reinforcement Exercises

HYDROSTATIC WEIGHING EQUATION DERIVATION

We arrived at equation (1) by starting with the definition of density as mass divided by its volume:

$$\rho = \frac{m_O}{V_O}$$

We can find the mass of an object if we divide its weight by *g:*

$$m = \frac{W_O}{g}$$

Inserting that result for mass into the density equation we have:

$$\rho = \frac{W_O}{gV_O}$$

For a completely submerged object the volume of water displaced is equal to the volume of the object, so we can replace V_O with V_D.

$$\rho = \frac{W_O}{gV_D}$$

Using the definition of density again, we can replace the volume of water displaced with the displaced water mass (m_W) divided by water density (ρ_W).

$$\rho = \frac{W_O}{g(m_D/\rho_W)} = \frac{W_O}{gm_D}\rho_W$$

We can look up the density of water, but it depends on the water temperature, which is why its important to measure the water temperature when hydrostatic weighing. Notice that we happen to have the mass of displaced water multiplied by **g** in the previous equation. That is exactly how we calculate the weight of the displaced water (W_D), so we can make that substitution:

$$\rho = \frac{W_O}{W_D}\rho_W$$

Archimedes' Principle which tells us that the *buoyant force pushing upward on objects in a fluid is equal to the weight displaced fluid.* Therefore we can replace W_D with F_B.

$$\rho = \frac{W_O}{F_B}\rho_W$$

We have learned that the difference between an object's weight (W_0) and apparent weight (W_A) tells us the size of the buoyant force (F_B), as long as the body is in static equilibrium (holding still):

$$F_B = W_O - F_A$$

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Making that replacement in our density equation we have:

$$\rho = \frac{W_O}{W_O - F_A}\rho_W$$

We now have an equation that allows us to calculate the density of an object by measuring only its weight and apparent weight, as long as we know the density of the fluid we are using.

CHAPTER 34.

UNIT 4 REVIEW

Key Terms and Concepts

Mass

Volume

Density

Weight

Hooke's Law

Spring Constant

Apparent Weight

Static Equilibrium

Net Force

Buoyant Force

Archimedes' Principle

Hydrostatic Weighing

Specific Gravity

Learner Outcomes

1. Compare and contrast mass, volume, density, weight and apparent weight and explain how each are measured.[2]
2. Apply the concept of static equilibrium to determine the magnitude and direction of unknown forces.[3]
3. Apply Archimedes' principle and density concepts to predict if objects will sink or float.[2]
4. Determine density from mass and volume measurements and using by hydrostatic weighing.[4]

CHAPTER 35.

UNIT 4 PRACTICE AND ASSESSMENT

Outcome 1

1) Which has greater density between a kilogram of feathers and a kilogram of pennies? Which has greater volume? Which has greater mass?

2) What is the weight in Newtons of a 3 **kg** textbook?

3) (a) Convert your own weight from pounds to Newtons.
(b) Then calculate your mass in kilograms. Show all work.

4) The acceleration due to gravity (*g*) on the moon is 1/6 that on the surface of Earth.
(a) Based on your answers to the previous question, what would your weight be on the moon?
(b) What would your mass be on the moon?

Outcome 2

5) For each object below, draw a free body diagram:
a) A car hanging from a crane (there are two forces).
b) A car skidding to a stop (there are three forces).
c) A car with the parking brake set being pushed on by a someone, but not moving (there are four forces here, but two of them are the same type).

6) A person stands on a scale.
a) What type of force is pulling them down?
b) What type of force is provided by the scale to hold them up?
c) Draw a free body diagram of this situation.

7) A 7 **N** force pushes on an object to the right and a 7 **N** force pushes on the object to the left.
(a) What is the net force?
(b) Can the object be in static equilibrium?

8) A 5 **N** force pushes on an object to the right and a 7 **N** force pushes on the object to the left.
(a) What is the net force?

(b) Can the object be in static equilibrium?

9) You push on a large box with 120 **N** of force, but it doesn't move.
(a) How large is the friction force?
(b) Draw a free body diagram of the situation.

Outcome 3

10) You are helping a 48 **lb** toddler learn to float in a swimming pool.
(a) What weight of water must the toddler displace in order to float?
(b) What volume of water must the toddler displace in order to float?
(c) Currently the toddler doesn't like water to cover his ears and holds his head mostly out of the water. You notice that it feels as though he only weighs 3 **lbs**. Draw a free body diagram of the situation.
(d) How large is the buoyant force on the toddler?
(e) If the toddler were to lower his head fully half-way into the water (past the ears), he would displace another 0.4 gallons worth of water**.** Would the toddler float then? [Hint: Water as a weight density of 8.34 **lbs/gal**]

11) An object has a volume of 0.5 $\mathbf{m^3}$ and weight of 150 **N**.
(a) What is the maximum volume of water it can displace?
(b) What weight of water can it displace?
(c) Will it float?
(d) Is the object in the previous problem more or less dense than water?

Outcome 4

12) Calculate the density of the object referred to in the previous problem.
13) An object has a weight of 5.5 **N** and an apparent weight of 3.5 **N** when fully submerged.
(a) Will the object float?
(b) Calculate the density of the object.

PART V.

UNIT 5: MAINTAINING BALANCE

Learner Objectives

1. Define center of gravity, support base, normal force, static friction and kinetic friction.[2]
2. Compare the relative torque applied to objects by various forces.[2]
3. Identify the type of equilibrium exhibited by various structures and rank their relative stability.[2]
4. Apply static equilibrium concepts to determine forces in physical situations, including normal force and friction.[3]

CHAPTER 36.

BALANCE

Warning sign indicating a rough walking surface, which isn't a problem for animals with more stable body types, such as cats and dogs. Image Credit: National Park Service

[1]

As an RN on MED floor, Jolene assesses each patient's fall risk according to the Morse Fall Scale, provide a nursing diagnosis (ND) for fall risk, and implement fall precautions based on the ND. The human body typically operates in many positions that are not very stable and we must constantly use our muscles to adjust our body position and counteract the tendency of our bodies to fall over. We often refer to this skill as *balance*. For the most part balance is subconscious, but watching a toddler who has just learned to walk will provide an amplified idea of how much actual work is required for humans to stay upright. Toddlers are especially unstable due to their disproportionately massive heads, and after this unit we will understand exactly why that feature so greatly affects their stability.

1. "Rough Surface Warning"National Park Service is in the Public Domain

CHAPTER 37.

CENTER OF GRAVITY

FINDING THE CENTER OF GRAVITY

You may have heard the term center of gravity in reference to balance and you might intuitively know that a toddler's big head raises their center of gravity, which makes them less stable than adults. We already know that the force of gravity is what gives an object weight, but what is the center of gravity? Think about which body part you feel gravity pulling on. Do you feel it pulling on just your leg, or your arm, or what? Actually, the force of gravity acts on all of your mass in the same way, according to Newton's Universal Law of Gravitation down to every single molecule and atom. If we break up your body into many many small chunks of equal mass we could calculate the tiny force of gravity on each one. If we add up all those tiny forces we get your total weight. If we average the locations of all those equal tiny forces, the resulting location would be the center of gravity. If we averaged the location of all the equal chunks of mass that would be the center of mass. Everyday objects, like humans, are small enough that gravity acts uniformly on all parts of the object and the center of gravity and the center of mass are essentially the same location. Check out the following video to learn how to experimentally find the center of gravity (mass) of an irregular object.

Reinforcement Exercises

BALANCE

Being out of balance means that your center of gravity is no longer above your support base (usually the space between your feet). When that happens you either fall down or take a step to widen your support base (regain your balance). Let's examine why those are the only two options you have.

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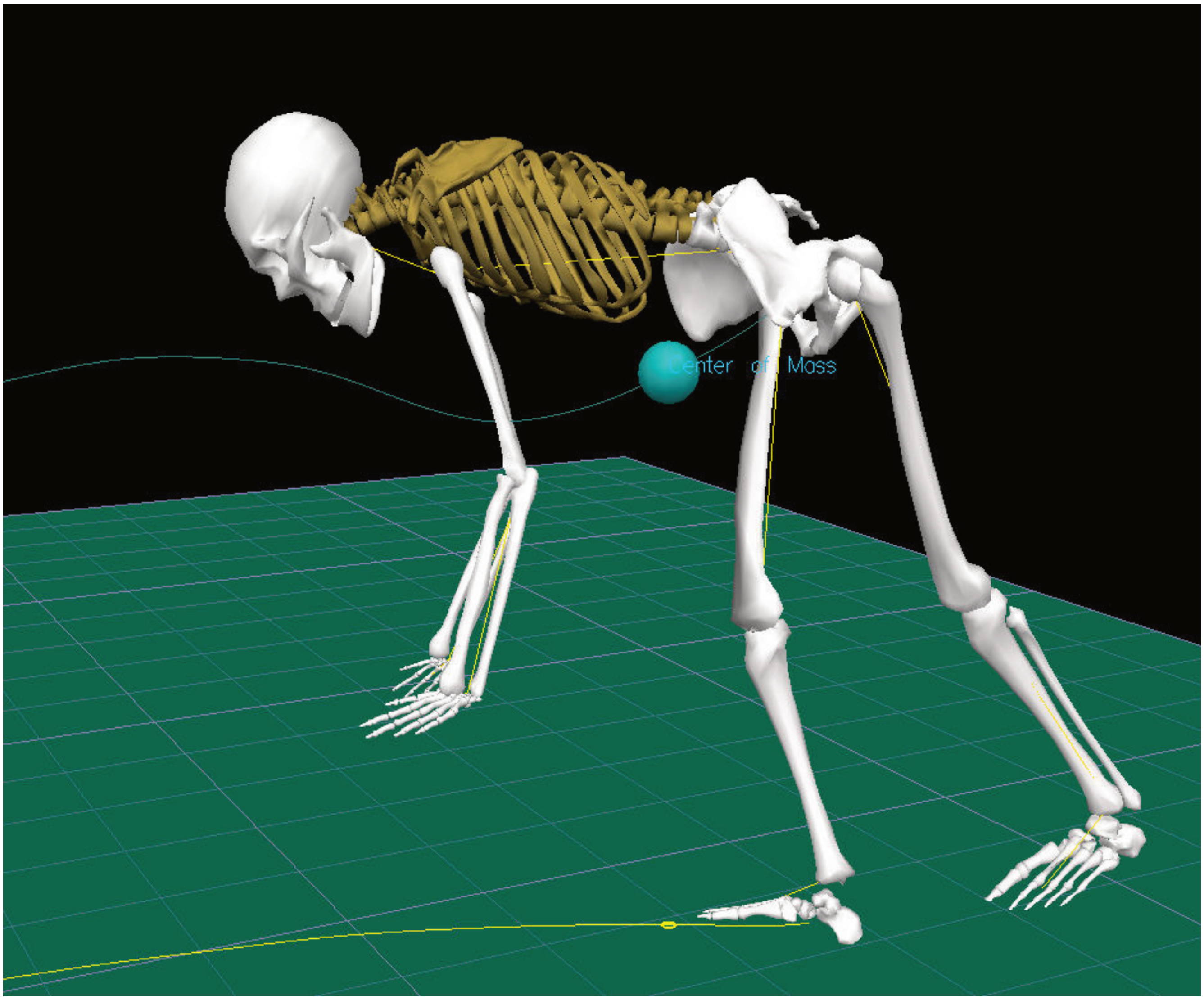


The center of gravity of an object (blue dot) is the average location of all gravitational forces. This average location does not necessarily have to be on the object. Image Credit: D. Gordon E. Robertson via wikimedia commons

[1]

Freely rotating objects tend to rotate around their center of mass. The following video shows a neat demonstration of that phenomenon:

https://youtu.be/DY3LYQv22qY

1. "COM" by D. Gordon E. Robertson, Wikimedia Commons is licensed under CC BY-SA 3.0

CHAPTER 38.

SUPPORTING THE BODY

SUPPORT FORCE (NORMAL FORCE)

When standing on the ground gravity is pulling you down, but you aren't falling. In fact you are in static equilibrium so the ground must be providing a supporting force that balances your weight. The ground provides that force in response to compression caused by your weight. When solid objects push back against forces that are deforming them we call that responsive push-back the Normal Force.

Reinforcement Activity

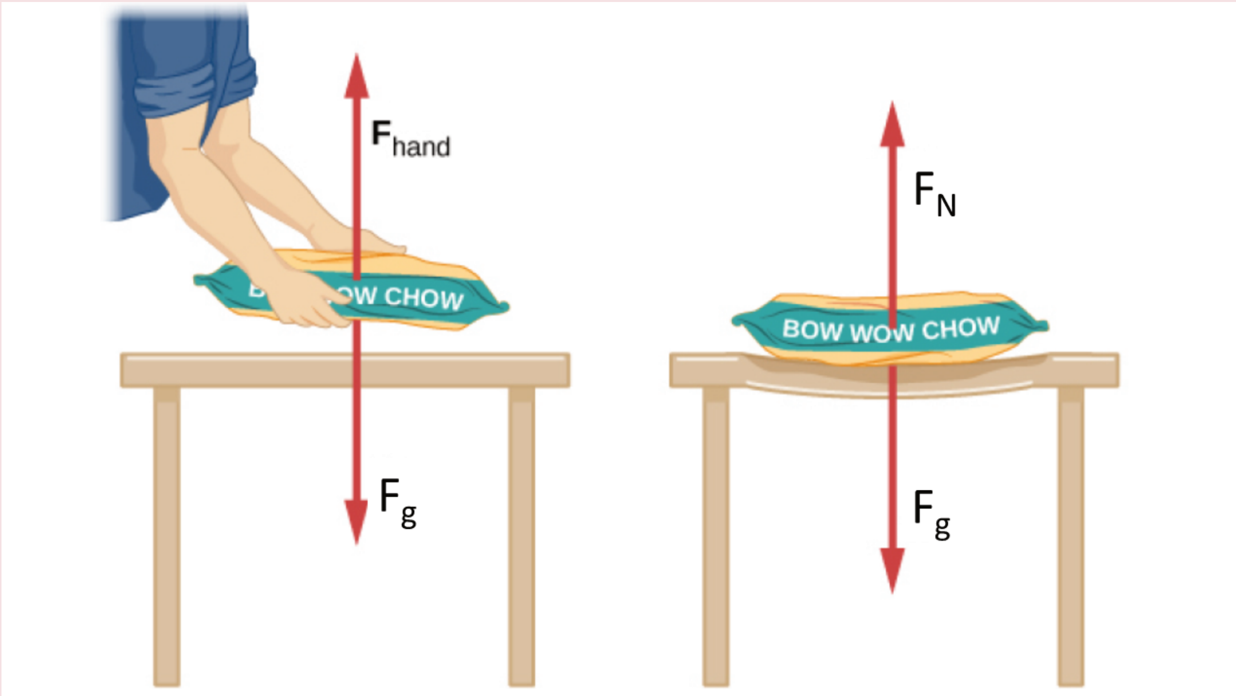
Push your finger down into your palm and feel the resistance from your palm.

That resistance is the normal force.

The normal force is a reactive force, meaning it only exists in response to a push from another object. When you pull your finger away from your palm, the normal force from your palm goes away.

Everyday Example[1]

In the diagram below, we see a person placing a bag of dog food on a table. When the bag of dog food is placed on the table, and the person lets go, how does the table exert the force necessary to balance the weight of the bag? While you wouldn't see it with your naked eye, the table sags slightly under the load (weight of the bag). This would be noticeable if the load were placed on a thin plywood table, but even a sturdy oak table deforms when a force is applied to it. That resistance to deformation causes a restoring force much like a deformed spring (or a trampoline or diving board). When the load is placed on the table, the table sags until the restoring force becomes as large as the weight of the load, putting the load in equilibrium. The table sags quickly and the sag is slight, so we do not notice it, but it is similar to the sagging of a trampoline or a hammock when you climb on.



The person holding the bag of dog food must supply an upward force equal in size and opposite in direction to the force of gravity on the food. The card table sags when the dog food is placed on it, much like a stiff trampoline. Elastic restoring forces in the table grow as it sags until they supply a normal force equal in size to the to the weight of the load. Image credit: University Physics

NORMAL FORCE AND WEIGHT

If you place an object on a table the normal force from the table supports the weight of the object. For this reason normal force is sometimes called support force. However, normal is another word for perpendicular, so we will stick with normal force because it reminds us of the important fact that the normal force always acts at an angle of 90° to the surface. That does not mean the normal force always point vertically, nor is it always equal to an object's weight. If you push horizontally on the wall, the wall pushes back (keeping your hand from moving through the wall). The force from the wall is a normal force, but it acts horizontally and is not equal to your weight.

Situations where normal force is not equal to the weight of the object. Adapted from Garscon Plancher" by Obiwancho, and "Trek on the Viedma Glacier" by Liam Quinn "U.S. Air Force Chief Master Sgt. Suzan Sangster"released by the United States Armed Forces with the ID 090815-F-3140L-048

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In each situation pictured above the normal force is not equal to body weight. In the left image the normal force is less than body weight, and acting horizontally. In the middle image the normal force is less than body weight and acting at an angle. In the right image the normal force on the drill is more than it's own weight because Master Sgt. Sangster is also pushing down on the drill. The normal force on Master Sgt. Sangster's feet is less than her weight because she is also receiving an upward normal force from the drill handle.

Often (*N*) is used as a symbol for normal force, but we are using **N** to abbreviate for the SI force unit Newtons, so instead we will use F_N. The normal force comes up so often students often accidentally begin to refer to normal force as "natural force" instead, so watch out for that possible source of confusion.

Reinforcement Exercises: Normal Force

2. "Garscon Plancher" by Obiwancho , Wikimedia Commons is licensed under CC BY-SA 3.0
3. "U.S. Air Force Chief Master Sgt. Suzan Sangster", Wikimedia Commons is in the Public Domain,
4. "Trek on the Viedma Glacier" by Liam Quinn , Wikimedia Commons is licensed under CC BY-SA 2.0

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CHAPTER 39.

SLIPPING

SLIPPING

Slipping happens when friction between feet and walking surface is not large enough to prevent your back foot from sliding as it pushes off, or the front foot from sliding when it tries to slow the forward motion of your center of gravity). Together, normal force and friction (F_f) provide the forces necessary to support the body and maintain balance. For example, friction prevents crutches from sliding outward when they aren't held perfectly vertical. Friction is also necessary for locomotion, such as walking and running, as we will learn in the Locomotion unit.

Friction between the crutches and the floor prevents the young boy's crutches from sliding outward even when they aren't held straight vertical. This 1942 photo by Fritz Henle was captioned "Nurse training. Using the picture book as bait, the physical therapist encourages a young victim of infantile paralysis [Polio] to learn to use his catches (crutches)." Polio was effectively eradicated from the United States by the polio vaccine, originally developed by Jonus Salk "who never patented the vaccine or earned any money from his discovery, preferring it be distributed as widely as possible." There are two types of vaccine that can prevent polio: inactivated poliovirus vaccine (IPV) and oral poliovirus vaccine (OPV). Only IPV has been used in the United States since 2000 and 99% of children who get all the recommended doses of vaccine will be protected from polio.

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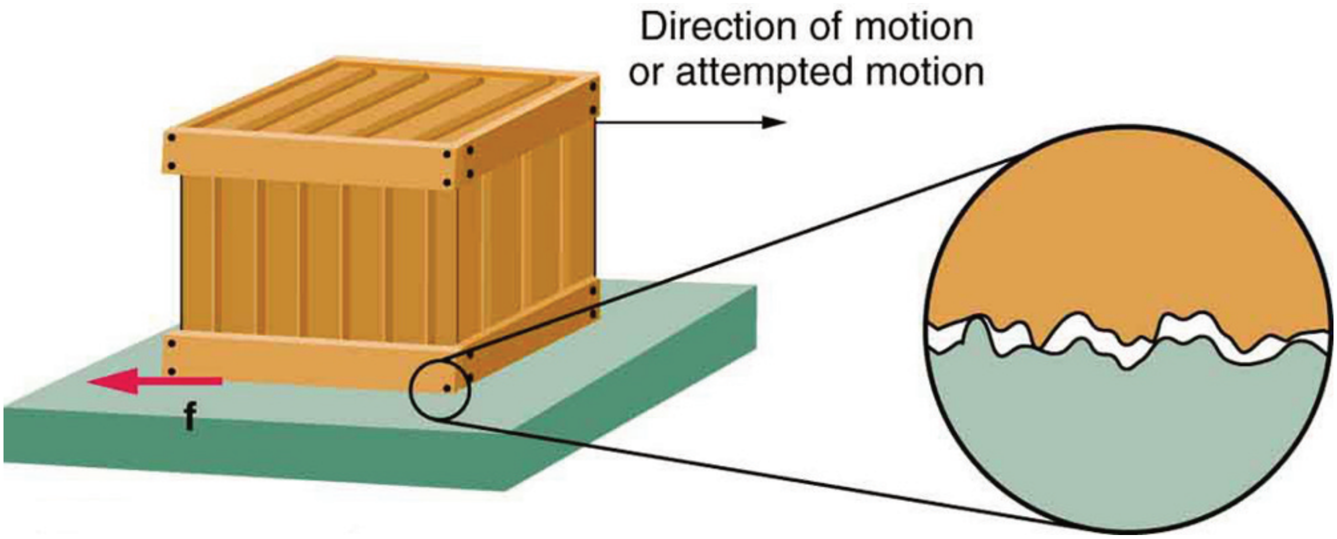
1. "Photo" by Fritz Henle, Library of Congress is in the Public Domain
2. "History of Salk" by The Salk Institute

FRICTION

Friction (F_f) is the force that resists surfaces sliding against one another. Rub your palms together, the resistance you feel is friction. Complimentary to normal force, which only points perpendicular to surfaces, friction only points parallel to surfaces.



Frictional forces always oppose motion or attempted motion between objects in contact. Friction arises in part because of the roughness of the surfaces in contact, as seen in the expanded view. In order for the object to move, it must rise to where the peaks can skip along the bottom surface. Thus a force is required just to set the object in motion. Some of the peaks will be broken off, also requiring a force to maintain motion. Much of the friction is actually due to attractive forces between molecules making up the two objects, so that even perfectly smooth surfaces are not friction-free. Such adhesive forces also depend on the substances the surfaces are made of, explaining, for example, why rubber-soled shoes slip less than those with leather soles.

Friction can only exist when two objects are attempting to slide past one another, so it is also reactive like normal force. Two surfaces must touch to have friction, so you also can't get friction without normal force. In fact, frictional force is proportional to normal force.

Reinforcement Activity

Rub your palms together. Now push your palms together hard and try to slide them at the same time.

Now the normal force is larger causing the frictional force to grow in proportion.

STATIC FRICTION

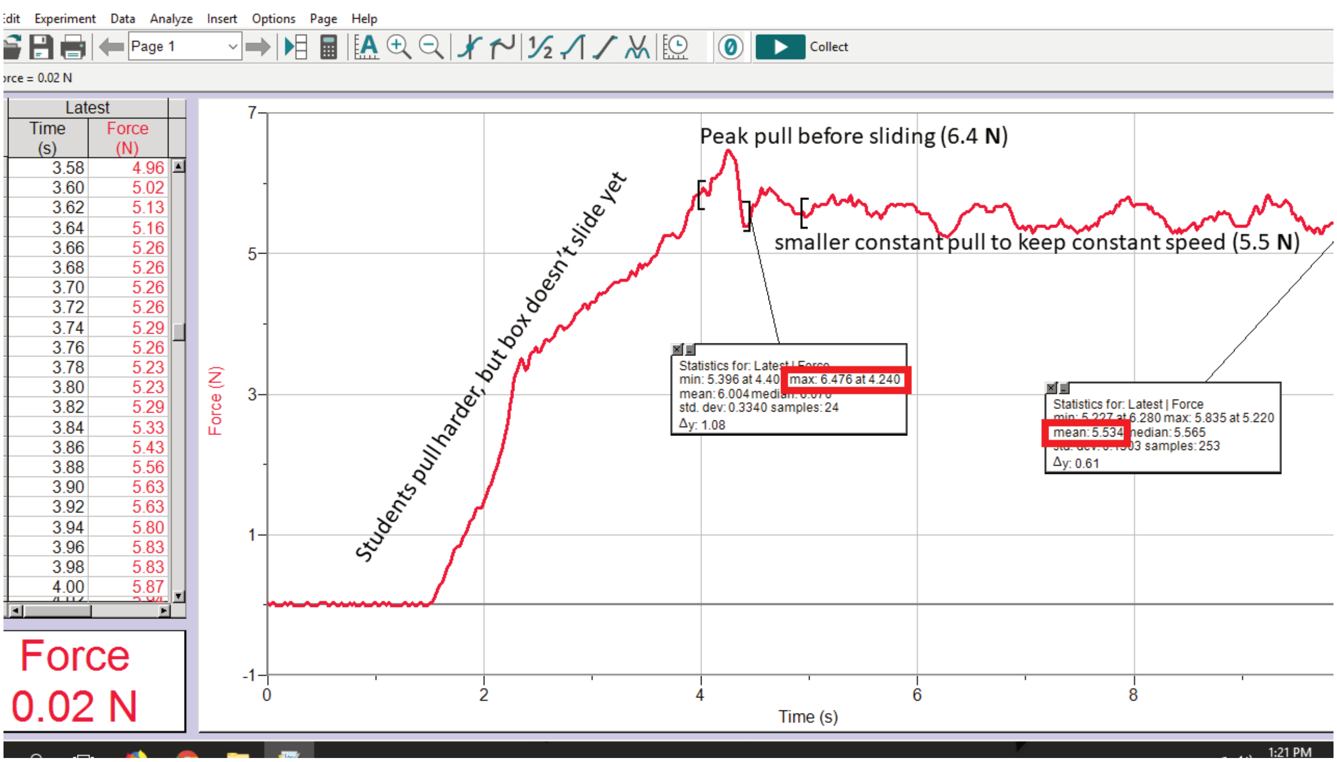
There are two categories of friction. Static friction($F_{f,s}$) acts between two surfaces when they are attempting to slide past one another, but have not yet started sliding. Static friction is a reactionary force because it only exists when some other force is pushing an object to attempt to cause it to slide across a surface. Static friction adjusts to maintain equilibrium with whatever other force is doing

3. "What is Polio" by Global Heatlh, Center for Disease Control

the pushing or pulling, but static friction has a maximum value. If the applied force gets larger than the maximum static frictional value, then static friction can't maintain equilibrium and the object will slide.

KINETIC FRICTION

Kinetic friction ($F_{f,k}$) acts whenever two surfaces are sliding past one another, whether or not some other force is pushing the object to keep it sliding. If there is not another force pushing the object to keep is sliding, then kinetic friction will eventually stop the sliding object, but we will learn more about that later. Static friction is larger than kinetic friction. The following graph of force vs. time demonstrates the process of breaking free of static friction when pulling on an object. The graph was created by measuring the force that students applied to a box sitting on a table by pulling on a string tied to the box.



Pull force applied to a box on a table. The students pulled lightly at first, then increasingly harder until the box began to slide, and then pulled just right to keep the box moving at constant speed. Notice that as the students pull harder the box has not yet move, which means the static frictional responds and grows larger to maintain static equilibrium. A maximum of static frictional force of 6.4 **N** *is reached before the box begins to slide and kinetic friction takes over. We see that the force drops at this point, meaning that the students had to reduce their pull force to 5.5* **N** *in order to just balance kinetic friction and maintain a constant speed. This demonstrates that kinetic friction is smaller than static friction. This data is was acquired by Umpqua Community College physics students Libby Fregoso and McKenzie Carrier.*

Choose the friction simulation from the simulation set to see how static and kinetic friction behave.

Reinforcement Activity

FRICTION COEFFICIENT

We now know that friction force is proportional to normal force and that there are two types of friction, static and kinetic. The final concept that affects friction is the roughness, or alternatively the smoothness, of the two surfaces. The coefficient of friction (μ) is a unitless number that rates the roughness and is typically determined experimentally. The static frictional force is larger than the kinetic frictional forces because μ_s is larger than μ_k. Take a look at the table of static and kinetic friction coefficients found below. You can find more values in this massive table of static friction coefficients.

Table of static and kinetic friction coefficients for various surface pairs[4]

System	Static friction, μ_s	Kinetic friction, μ_k
rubber on dry concrete	1.0	0.7
rubber on wet concrete	0.7	0.5
wood on wood	0.5	0.3
waxed wood on wet snow	0.14	0.1
metal on wood	0.5	0.3
steel on steel (dry)	0.6	0.3
steel on steel (oiled)	0.05	0.03
teflon on steel	0.04	0.04
bone lubricated by synovial fluid	0.016	0.015
shoes on wood	0.9	0.7
shoes on ice	0.1	0.05
ice on ice	0.1	0.03

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4. OpenStax University Physics, University Physics Volume 1. OpenStax CNX. Aug 2, 2018 http://cnx.org/contents/d50f6e32-0fda-46ef-a362-9bd36ca7c97d@11.1.

System	Static friction, μ_s	Kinetic friction, μ_k
steel on ice	0.4	0.02

Notice that two surfaces are always listed in the table; you must have two surfaces to define a μ. When someone asks a question like, "what is the μ of ice?" they usually mean between ice and ice, but its best to avoid asking such questions and just always reference two surfaces.

CALCULATING FRICTION FORCES

We can sum up everything we have learned about friction in two equations that relate the friction forces to the friction coefficient for two surfaces and the normal force acting on the surfaces:

Max static friction before release:

(1) $F_{f,s}^{max} = \mu_s F_N$

Kinetic friction once moving:

(2) $F_{f,k} = \mu_k F_N$

Everyday Example: Firefighter Physical Ability Test

Firefighter candidates must complete a physical ability test (PAT) that includes dragging a dummy across the floor. The PAT for the city of Lincoln Nebraska specifies that candidates must drag a human form dummy weighing 170 **lbs** for 25 feet, around a barrel, and then back across the starting point for a total distance of 50 feet in six minutes or less. The candidates may only drag the dummy using the pull harness attached to the dummy and cannot carry the dummy[5].

The test is held on a polished concrete floor. The static friction coefficient between cotton clothing and polished concrete is 0.5. If a candidate pulls vertically up on the harness with a force of 70 **lbs** what horizontal pull force must the candidate apply in order to get the dummy moving?

The dummy starts out in static equilibrium so we know the net force must be zero in both the veritical and horizontal directions. First, let's analyze the vertical direction: if the candidate pulls vertically up on the harness with a force of 70 **lbs** then the floor must provide a normal force of 100 **lbs** to support the dummy.

Now let's analyze the horizontal direction: static friction will match whatever horizontal pull the candidate provides, but in the opposite direction, so that the dummy stays in static equilibrium until the pull exceeds the max static friction force. That's the force the candidate needs to apply to get the dummy moving, so let's find that. We have the friction coefficient and we already found the normal force so we are ready:

$$F_{f,s}^{max} = \mu_s F_N = 0.5 \cdot 100\,\mathbf{lbs} = 50\,\mathbf{lbs}$$

After the dummy starts moving, kinetic friction kicks in so we can use $\mu_k = 0.4$ to calculate the kinetic frictional force. The is force is less than the max static frictional force, so it will require less force to keep the dummy moving than it did to get it started.

$$F_{f,k} = \mu_k F_N = 0.4 \cdot 100\,\mathbf{lbs} = 40\,\mathbf{lbs}$$

5. "Firefighter Physical Ability Test Candidate Orientation Guide" by Industrial/Organizational Solutions, Inc.

Reinforcement Exercises

A person clings to a playground fire pole. "Firepole" by Donkeysforever, via Wikimedia Commons is in the Public domain

The equations given for static and kinetic friction are empirical models that describe the behavior of the forces of friction. While these formulas are very useful for practical purposes, they do not have the status of laws or principles. In fact, there are cases for which these equations are not even good approximations. For instance, neither formula is accurate for surfaces that are well lubricated or sliding at high speeds. Unless specified, we will not be concerned with these exceptions.[6]

An interactive or media element has been excluded from this version of the text. You can view it online here:

https://openoregon.pressbooks.pub/bodyphysics/?p=4298

6. OpenStax University Physics, University Physics Volume 1. OpenStax CNX. Aug 2, 2018 http://cnx.org/contents/d50f6e32-0fda-46ef-a362-9bd36ca7c97d@11.1.

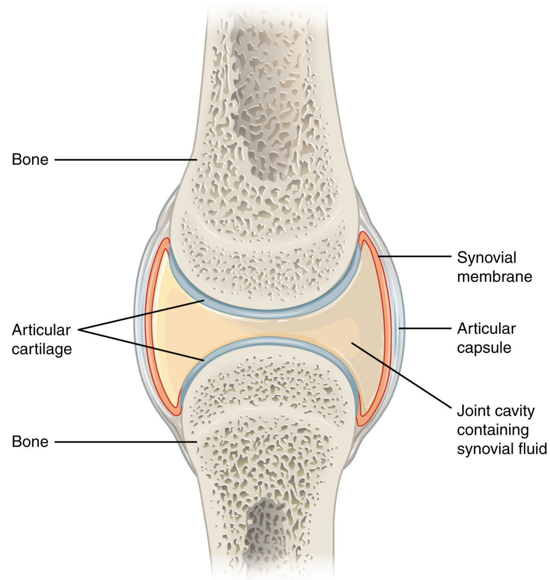
CHAPTER 40.

FRICTION IN JOINTS

SYNOVIAL JOINT FRICTION

Static and kinetic friction are both present in joints. Static friction must be overcome, by either muscle tension or gravity, in order to move. Once moving, kinetic friction acts to oppose motion, cause wear on joint surfaces, generate thermal energy, and make the body less efficient. (We will examine the efficiency of the body later in this textbook.) The body uses various methods to decrease friction in joints, including synovial fluid, which serves as a lubricant to decrease the friction coefficient between bone surfaces in synovial joints (the majority of joints in the body). Bone surfaces in synovial joints are also covered with a layer of articular cartilage which acts with the synovial fluid to reduce friction and provides something other than the bone surface to wear away over time[1]. We ignored friction when analyzing our forearm as a lever because the frictional forces are relatively small and because they acted inside the joint, very close to the pivot point so they caused negligible torque.

1. OpenStax, Anatomy & Physiology. OpenStax CNX. Jun 25, 2018 http://cnx.org/contents/14fb4ad7-39a1-4eee-ab6e-3ef2482e3e22@10.1.



Synovial joints allow for smooth movements between the adjacent bones. The joint is surrounded by an articular capsule that defines a joint cavity filled with synovial fluid. The articulating surfaces of the bones are covered by a thin layer of articular cartilage. Ligaments support the joint by holding the bones together and resisting excess or abnormal joint motions. Image Credit: OpenStax Anatomy & Physiology

Reinforcement Exercises

Find a value for the kinetic coefficient of friction between ends of a bone in a synovial joint lubricated by synovial fluid. State your value and your source.

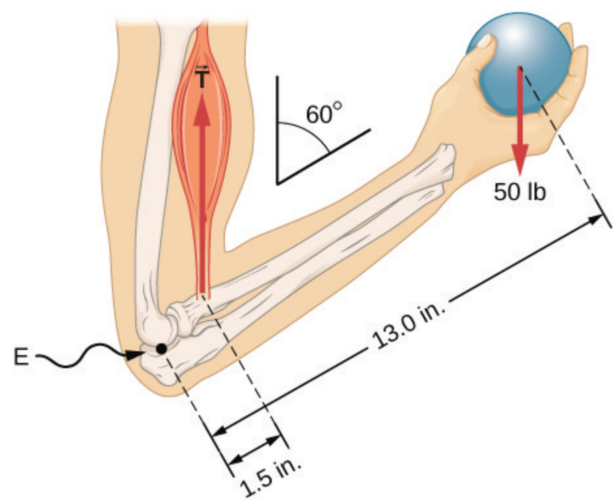
If the normal force between bones in the knee is 160 **lbs**, what is the kinetic frictional force between the surfaces of the knee bones?

CHAPTER 41.

TIPPING

TORQUE

When you hold an object in your hand, the weight of the object tends to cause a rotation of the forearm with the elbow joint acting as the pivot. The tension force applied by your biceps tries to counteract this rotation.



*The elbow joint flexed to form a 60° angle between the upper arm and forearm while the hand holds a 50 **lb** ball. The weight of the ball exerts a torque on the forearm about the elbow joint. Image Credit: Openstax University Physics*

[1]

When forces applied to an object tend to cause rotation of the object, we say the force is causing a torque. The size of a torque depends on the size of the force, the direction of the force, and the distance from the pivot point to where the force acts.

1. OpenStax University Physics, University Physics Volume 1. OpenStax CNX. Jul 11, 2018 http://cnx.org/contents/d50f6e32-0fda-46ef-a362-9bd36ca7c97d@10.18.

Reinforcement Activity

STATIC EQUILIBRIUM

In order for an object to remain still then any torques cancel each other out so that there is no net torque. If the net torque is not zero the the object will begin to rotate rather than remain still. For example, in our example of the forearm holding the ball, the torque due to biceps tension and torque due to ball weight must be equal, but in opposite directions.

Reinforcement Exercises

TIPPING POINT

When a body's center of gravity is above the area formed by the support base the normal force can provide the torque necessary to remain in rotational equilibrium.

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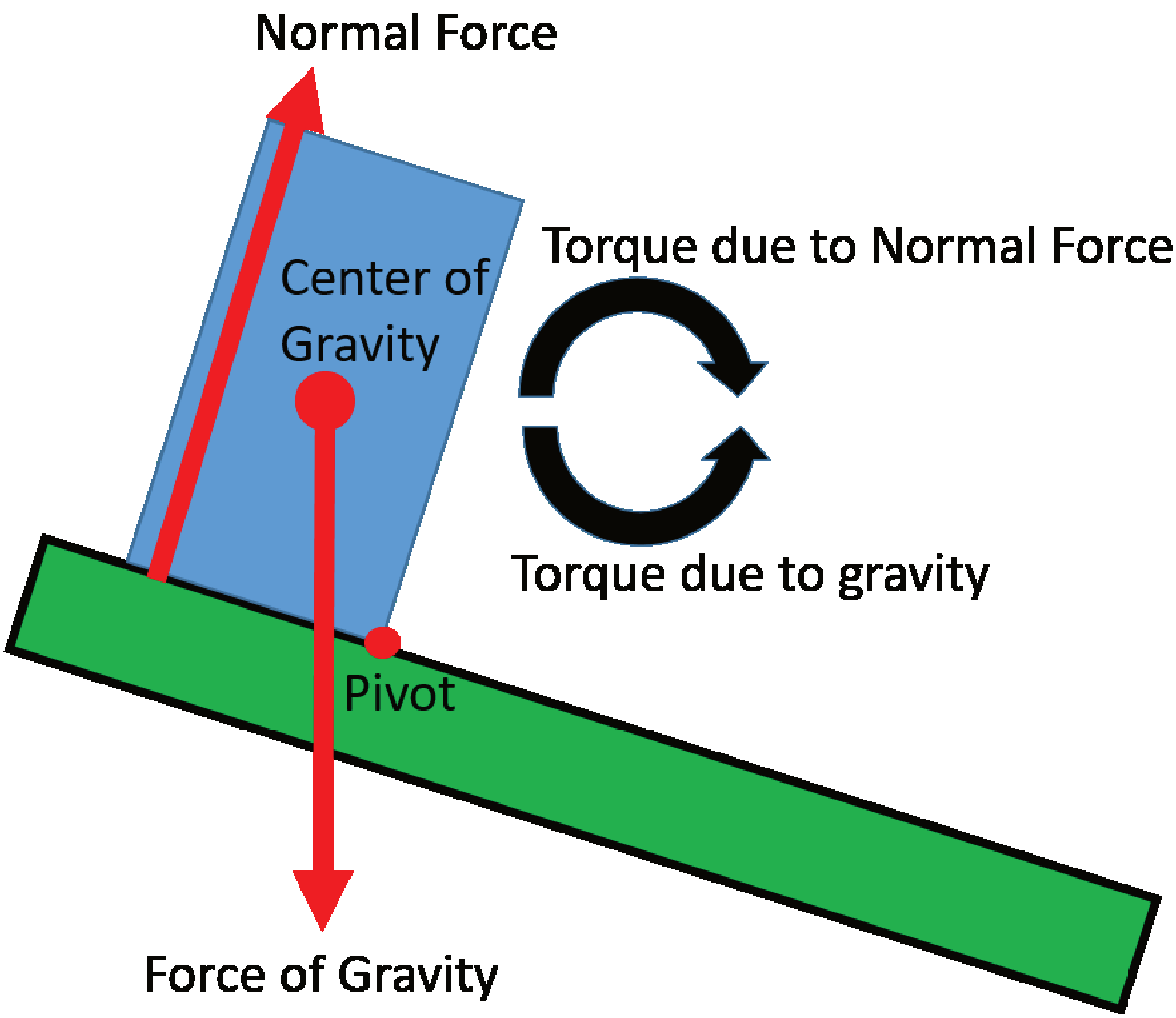
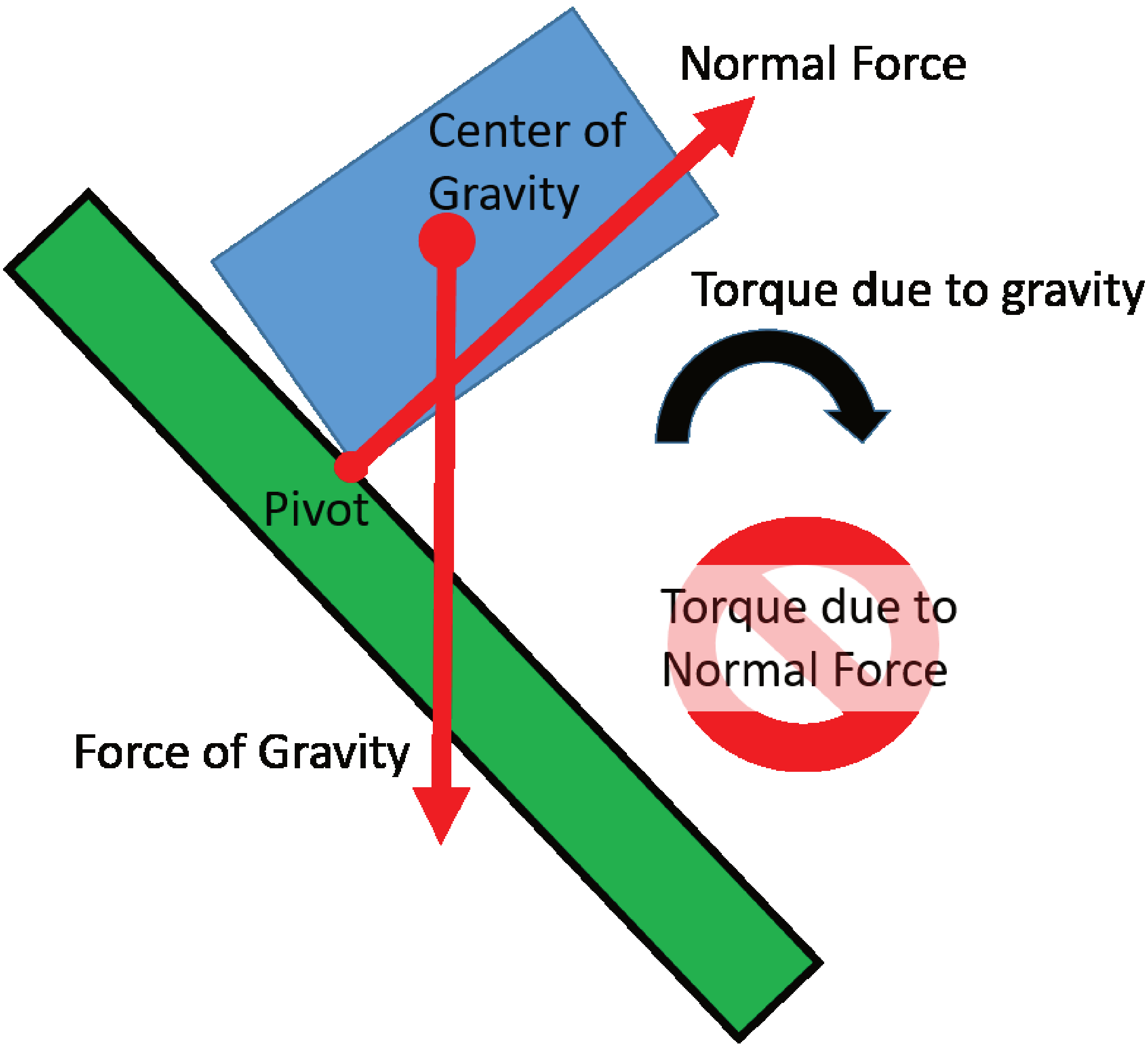


An object in rotational equilibrium. The torque from normal force cancels the torque from gravity. In this case friction (not shown) acts on the bottom surface of the object to keep it from sliding downhill.

The critical tipping point is reached when the center of gravity passes outside of the support base. Beyond the tipping point, gravity causes rotation away from the support base, so there is no normal force available to cause the torque needed to cancel out the torque caused by gravity. The normal force acting on the pivot point can help support the object's weight, but it can't create a torque because it's not applied at any distance away from the pivot.



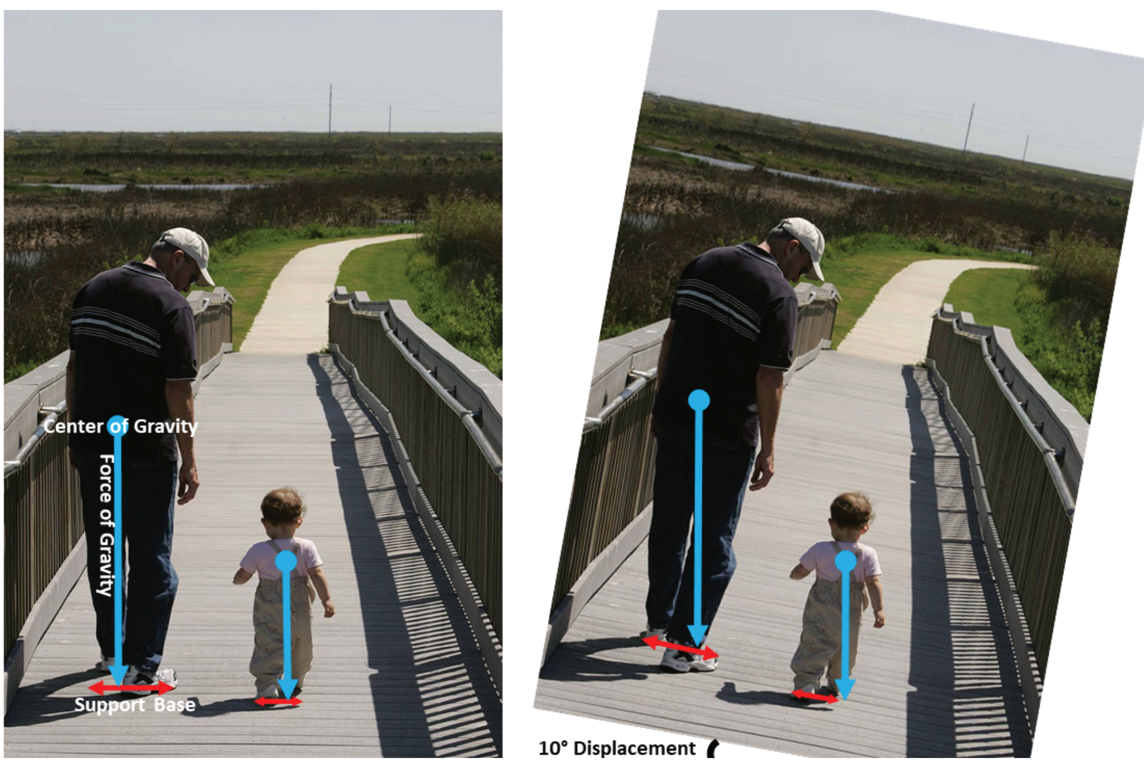
An object out of rotational equilibrium. The normal force acting at the pivot cannot produce a torque to cancel the torque caused by gravity. In this case friction (not shown) acts at the pivot point to keep the object from sliding downhill.

Now with a net torque the object can not be in rotational equilibrium. The object will rotate around the edge of the support base and tip over. We often refer to structures (and bodies) that are relatively resistant to tipping over as having greater stability.

CHAPTER 42.

HUMAN STABILITY

When asking what makes a structure more or less stable, we find that a high center of gravity or a small support base makes a structure less stable. In these cases a small displacement is need in order to move the center of gravity outside the area of support. Structures with a low center of gravity compared to the size of the support area are more stable. One way to visualize stability is to imagine displacement of the center of gravity caused by placing the object on a slope. For example, a 10° displacement angle might displace the center of gravity of a toddler beyond the support base formed by its feet, while an adult would still be in equilibrium.



Compared to an adult, a smaller displacement will move a toddlers center of gravity outside the base of support. Image adapted from A man and a toddler take a leisurely walk on a boardwalk by Steve Hillibrand via Wikimedia Commons.

[1]

The center of gravity of a person's body is above the pivots in the hips, which is relatively high compared to the size of the support base formed by the feet, so displacements must be quickly controlled. This control is a nervous system function that is developed when we learn to hold our bodies erect as infants. For increased stability while standing, the feet should be spread apart, giving a larger base of support. Stability is also increased by bending the knees, which lowers the center of gravity toward the base of support. A cane, a crutch, or a walker increases the stability of the user by widening the base of support. Due to their disproportionately large heads, young children have their center of gravity between the shoulders, rather than down near the hips, which decreases their stability and increases the likelihood of reaching a tipping point.[2]

Warning label on a bucket indicating the danger of children falling into a bucket and drowning. This danger is caused by the inherent instability of the toddler body. Image Credit: GodsMoon via Wikimedia Commons.

3

Reinforcement Exercises

1. " A man and toddler take a leisurely walk on a boardwalk" by Steve Hillebrand, U.S. Fish and Wildlife Service, Wikimedia Commons, is in the Public Domain
2. OpenStax, College Physics. OpenStax CNX. Aug 3, 2018 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@12.1.
3. "Drowning Child Warning" by GodsMoon, Wikimedia Commons is licensed under CC BY-SA 2.0

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CHAPTER 43.

TRIPPING

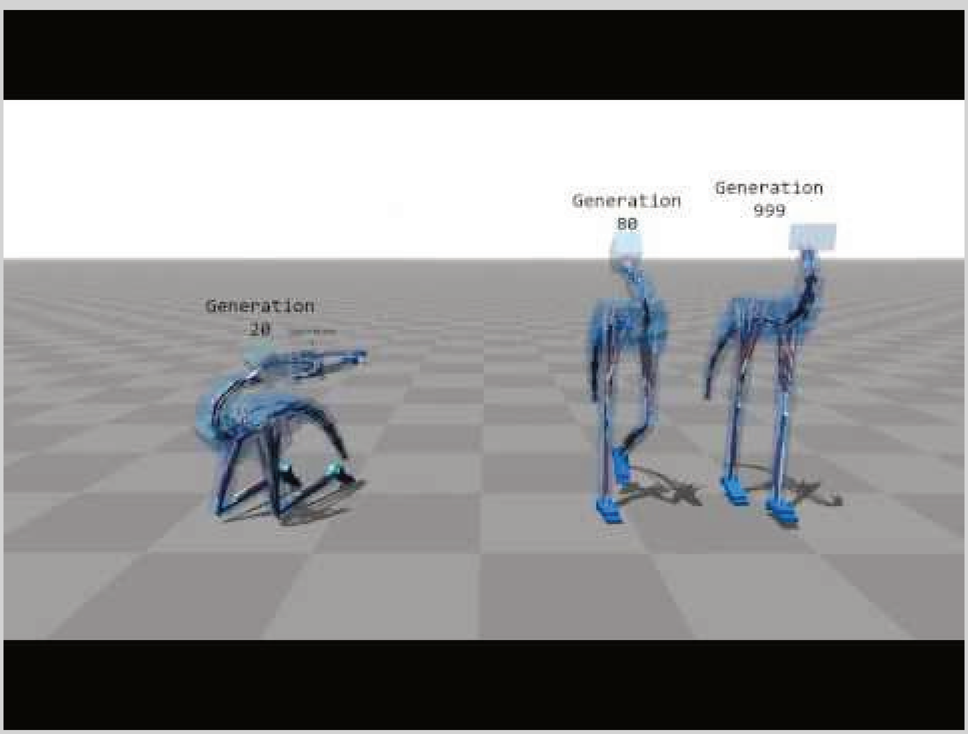
Walking is an act of moving in and out of equilibrium and we will learn more about walking in the unit on locomotion. In order to walk we:

1. Push against the ground with one foot using normal force and friction while leaning forward, lifting the other foot, and moving it forward. This moves the center of gravity passes outside the support base formed by the (now) back foot. Having passed the tipping point, the body would fall except:
2. The front foot lands, slowing the forward motion of your center of gravity and creating a new support base so that you are no longer past the tipping point. The front foot become the back foot and begins to pushes off.
3. Repeat.

Slipping happens when the friction coefficient between feet and walking surface is too small and the frictional force is not large enough to prevent your feet from sliding as the back foot pushes off and/or the front foot tries to slow the forward motion of your center of gravity.

Tripping happens when your foot does not move forward quickly enough to shift your support base below your center of gravity and you either fall over or have to rapidly move you feet into position just in time (stumble). Check you these AI simulations of creature that employ bipedal motion learning how to walk, and tripping along the way.

To see what AI algorithms can do when given a real physical body to experiment with, check out these robots.



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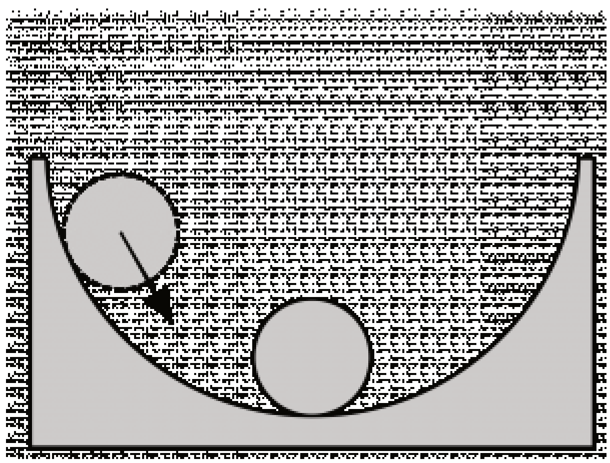
CHAPTER 44.

TYPES OF STABILITY

STABLE EQUILIBRIUM

If a structure is pushed out of equilibrium we say it has been displaced from equilibrium. If the object tends to move back toward its equilibrium position then it must be in a region of stable equilibrium and the force that pushed it back is a restoring force.



A marble in the bottom of a bowl is an example of stable equilibrium. Image credit: "Stable Equilibrium" by Urutseg, via Wikimedia Commons

1

As your arm hangs from your shoulder, it is in stable equilibrium. If your arm is lifted to the side and then let go it will fall back down to the hanging position. The hanging arm is a stable position because the center of gravity of the arm is located below the base of support, in this case the shoulder. When displaced (lifted a bit) the force of gravity acting on your arm will cause a torque that rotates your arm back down to the hanging position. In such cases, when an object is displaced from the equilibrium position and the resulting net forces (or torques they cause) move the object back toward the equilibrium position then these forces are called restoring forces. The sloth takes advantage of stable equilibrium to save energy that humans spend on staying upright. If the sloth is displaced in

1. "Stable Equilibrium" by Urutseg, Wikimedia Commons is in the Public Domain, CC0

any direction, the force of gravity automatically acts as a restoring force and returns the slot to its equilibrium position.

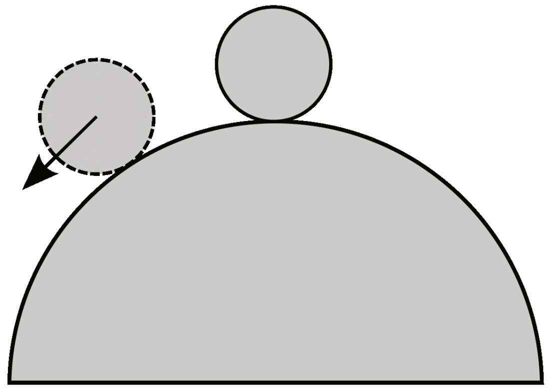
A two-toed sloth hangs from its feet in a stable equilibrium position. Image Credit: Two Toed Sloth by Cliff via Wikimedia Commons

2

UNSTABLE EQUILIBRIUM

When a system in equilibrium is displaced and the resulting net force pushes the object even further away from the equilibrium position then it must have been in an unstable equilibrium. Technically, real systems cannot spend time at unstable equilibrium point because the tiniest vibration will cause them to move out of equilibrium not to mention that you could never place them perfectly into position in the first place. Trying to balance a marble on a hill is a good example:

2. Two Toed Sloth (Choloepus didactylus) By Cliff [CC BY 2.0 (https://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons



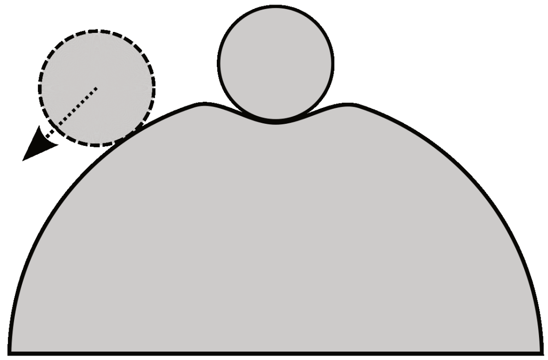
An example of unstable equilibrium is a marble placed on a hill. Image Credit: "Unstable Equilibrium" by Urutseg, via Wikimedia Commons.

[3]

METASTABLE EQUILIBRIUM

Some structures that are in stable equilibriumand can be displaced relatively far before they are no longer in equilibrium. Other structures structures that only require a small displacement to move out of equilibrium (like toddlers). We often call these systems stable and unstable, but this can be misleading because any standing structure is somewhat stable and a truly unstable structure would not stand still for any time. These structures that are in a stable region, but could be pushed passed a tipping point are known to be in a metastable equilibrium.

3. "Unstable Equilibrium" by Urutseg, Wikimedia Commons is in the Public Domain, CC0



The marble is in meta-stable equilibrium as long as it doesn't move outside the dip in the center. The peak at edge of the dip is analogous to the tipping point for a structure; beyond this point the marble will not move back toward the equilibrium position. Image credit: "Meta-stable Equilibrium" by Urutseg via Wikimedia Commons

[4]

Keeping your balance requires that you stay with the the stable region of a metastable equilibrium. For example, we expect that most people would say the person balancing on their head in the following image is unstable, but that wouldn't be quite accurate. Actually, the person is actively adjusting the shape of their body to shift their center of gravityto remain within the stable region of a metastable equilibrium, though it is a narrow one.

4. "Meta-stable Equilibrium" by Urutseg, Wikimedia Commons is in the Public Domain, CC0

A person in a barely-stable equilibrium. Image Credit: Usien via Wikimedia Commons.

5

Exercises

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5. By Usien [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], from Wikimedia Commons

CHAPTER 45.

THE ANTI-GRAVITY LEAN

GIF animation of the "anti-gravity lean" maneuver in which a person wearing shoes that attach to the floor can lean forward with straight legs and then return to a standing position. Image Credit: Asanagi via Wikimedia Commons

1

The structures discussed in the previous chapters were resting on the support base, which was not *attached* to the support surface (such as your feet and the ground). Therefore only normal force and friction were available to cancel torques caused by gravity and maintain equilibrium. When the support base is attached then tension can help cancel out gravitational torques and the structure can remain in equilibrium even when the center of gravity moves outside the area of support. Such structures are known as cantilevered structures. The animation above shows someone performing the "anti-gravity lean" during which the body is momentarily a cantilevered structure. The maneuver requires that the heels of the shoes be attached to the ground in order to provide a tension force. Cantilevered structures can generate especially large stress and strain on the materials in the structure. For example the Achilles' tendon is severely stressed during the anti-gravity lean. When stress becomes too great then rupture may occur. The following unit will apply what we have learned about static equilibrium to determine the size of forces acting on and withing the body when it isn't moving. The unit after that will calculate forces on the body when it is moving.

1. "Anti-gravity Lean" by Asanagi, Wikimedia Commons

CHAPTER 46.

UNIT 5 REVIEW

Key Terms and Conepts

Center of Gravity

Normal Force

Friction

Coefficient of friction

Reactive forces

Torque

Rotational Equilibrium

Stable Equilibrium

Unstable Equilibrium

Metastable Equilibrium

Stability

Learner Objectives

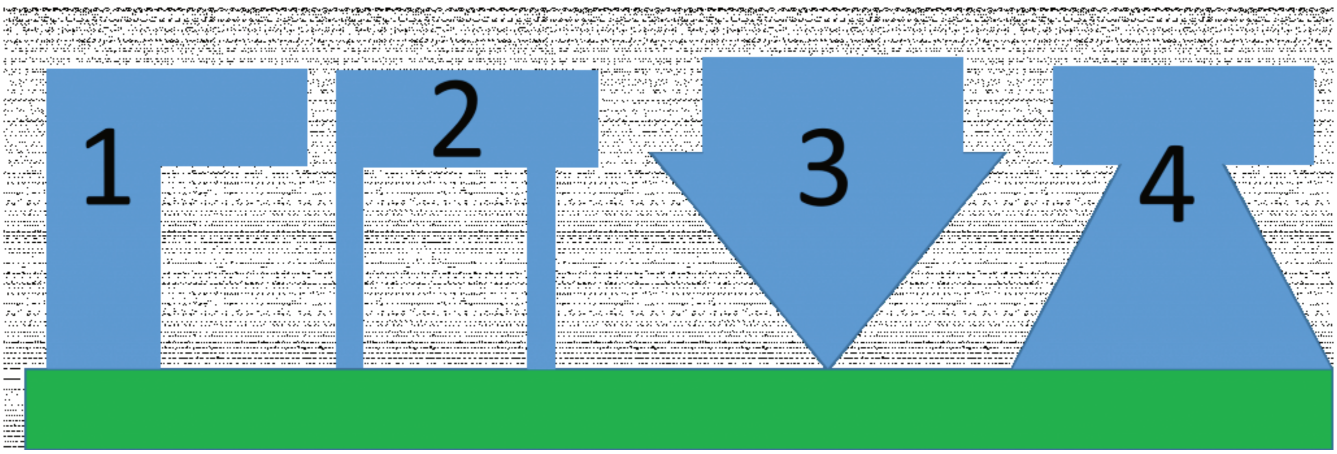
1. Define center of gravity, support base, normal force, static friction and kinetic friction.[2]
2. Compare the relative torque applied to objects by various forces.[2]
3. Identify the type of equilibrium exhibited by various structures and rank their relative stability.[2]
4. Apply static equilibrium concepts to determine forces in physical situations, including normal force and friction.[3]

CHAPTER 47.

UNIT 5 PRACTICE AND ASSESSMENT

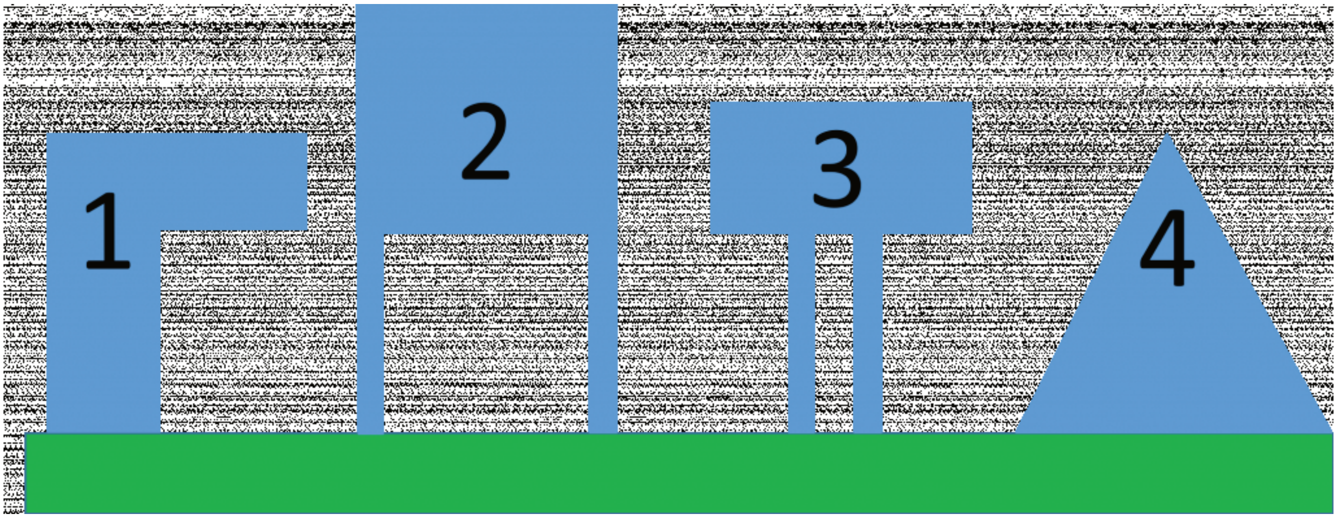
Outcome 1

1) Rank the structures below in order of increasing support base width.



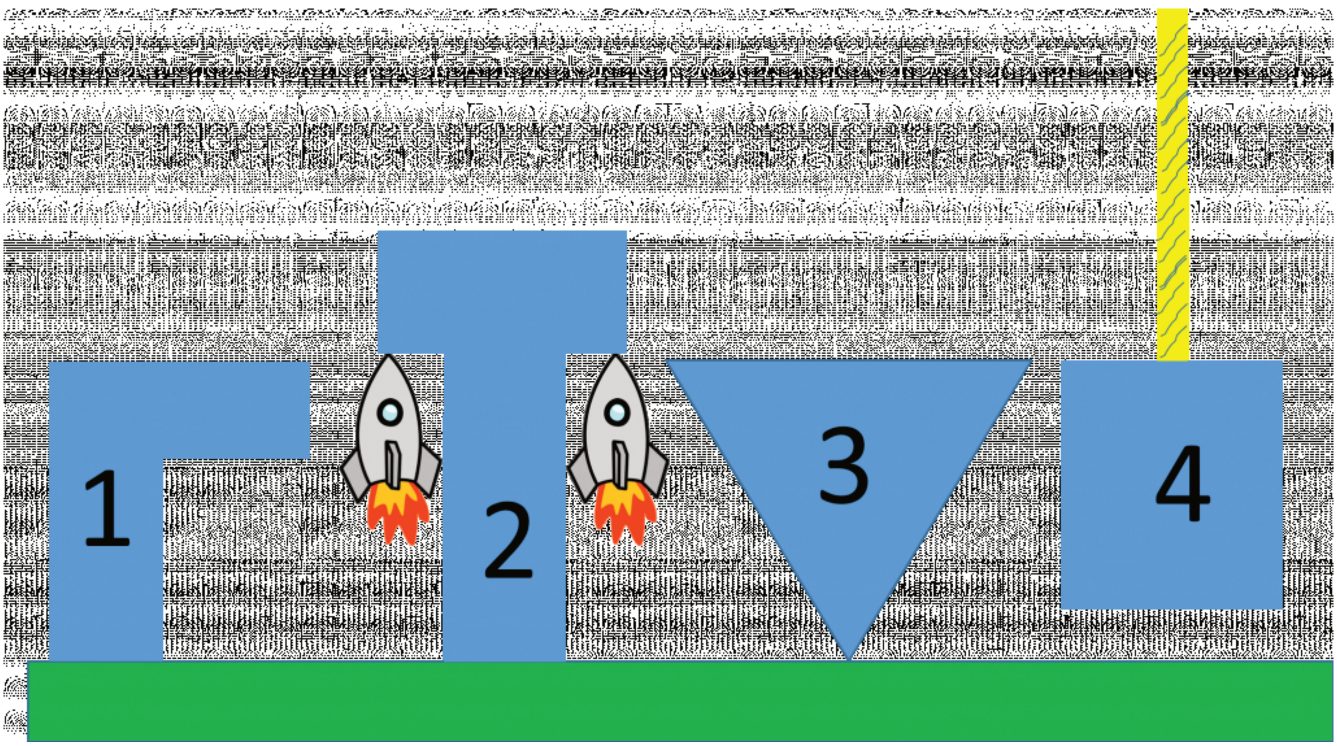
Four structures of equal height, but varying shape and base width.

2) Rank the structures below in order of increasing center of gravity height. All four structures are solid and are made of the same material.



Four structures of equal mass, but varying height and base width.

3) Rank the structures below in order of increasing normal force from the ground. All four structures have the same weight and are at rest.

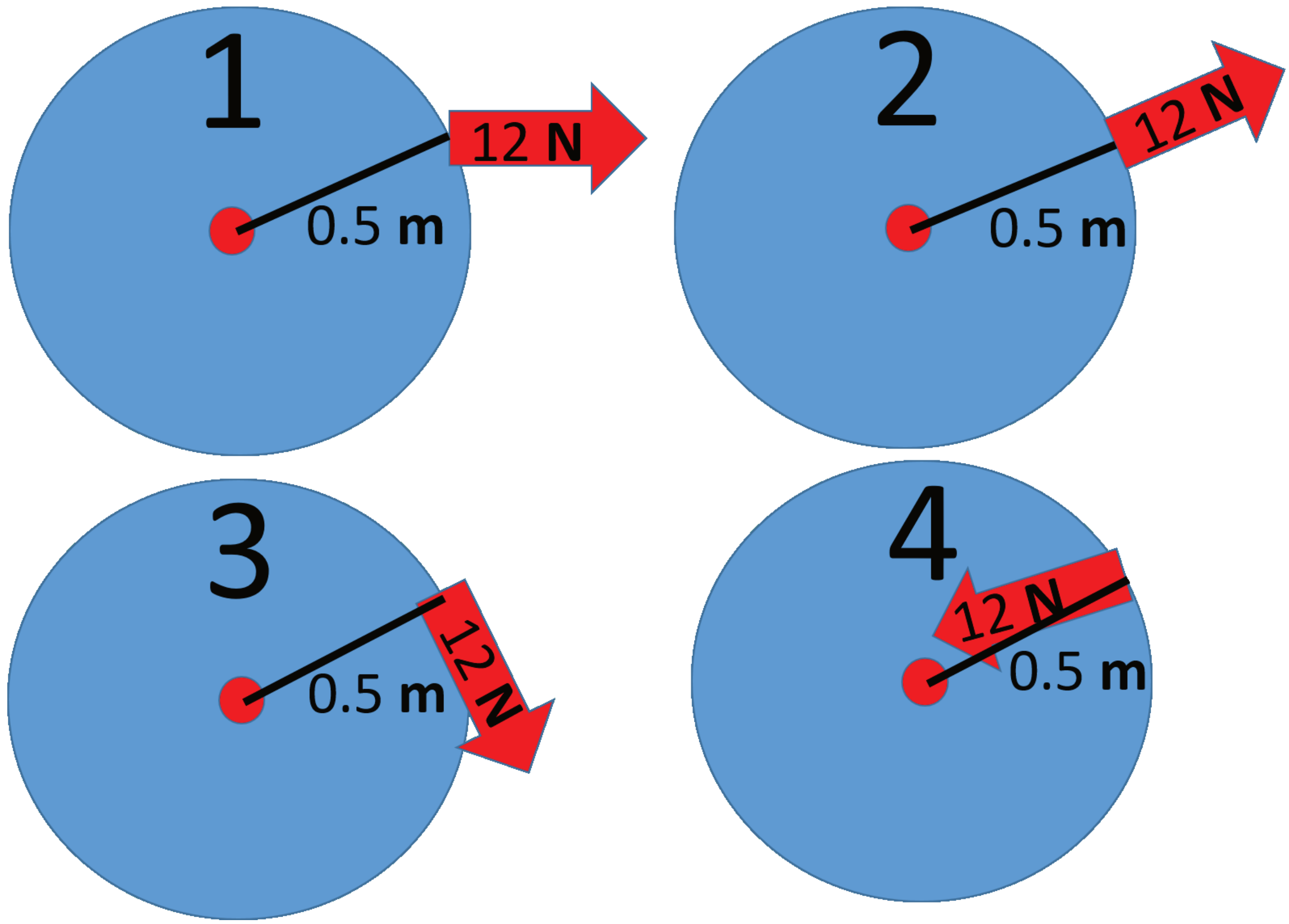


Four structures of equal weight. The second structure has rockets pushing up on it and the fourth structure is hanging from a rope. Rocket images from http://wpclipart.com are in the Public Domain.

Outcome 2

5) A child at a playground pushes on a large disk that rotates on an axle trough its center. The child

tries pushing on the edge of the disk in several different directions, as indicated by the top-down diagrams below. Rank the child's attempts by the amount of torque applied to the disk, from least to greatest.

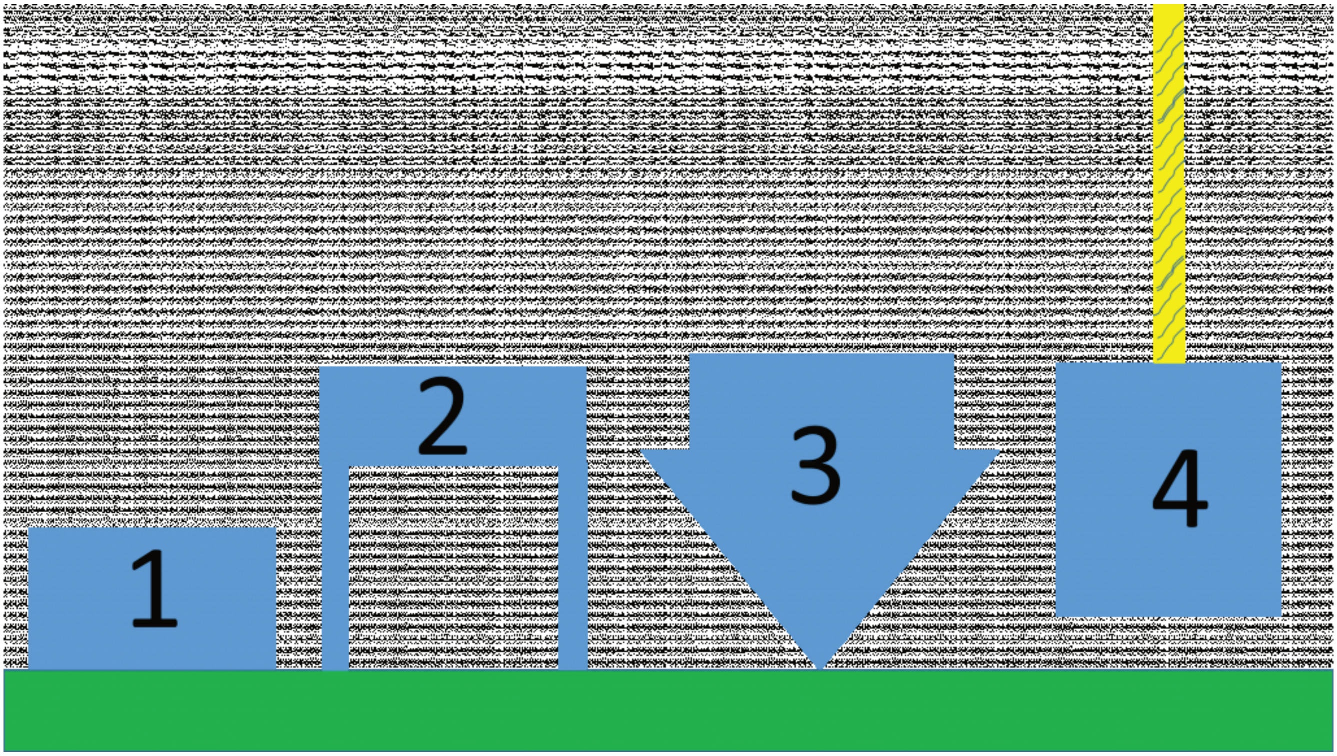


Four disks 0.5 m radius, each with a 12 N force applied at the edge. Disk 1 has the force applied outward at a slight angle to the radius. Disk two has the force applied outward directly along the radius. Disk 3 has the force applied perpendicular to the radius. Disk four has the force applied at a slight angle to the radius, but inward. The angle with the radius is smaller than the angle in disk 1.

6) If the child in the previous problem was able to apply a 12 **N** force and the disk had a 0.5 **m** radius, what would be the value of the torque applied in trial 3?

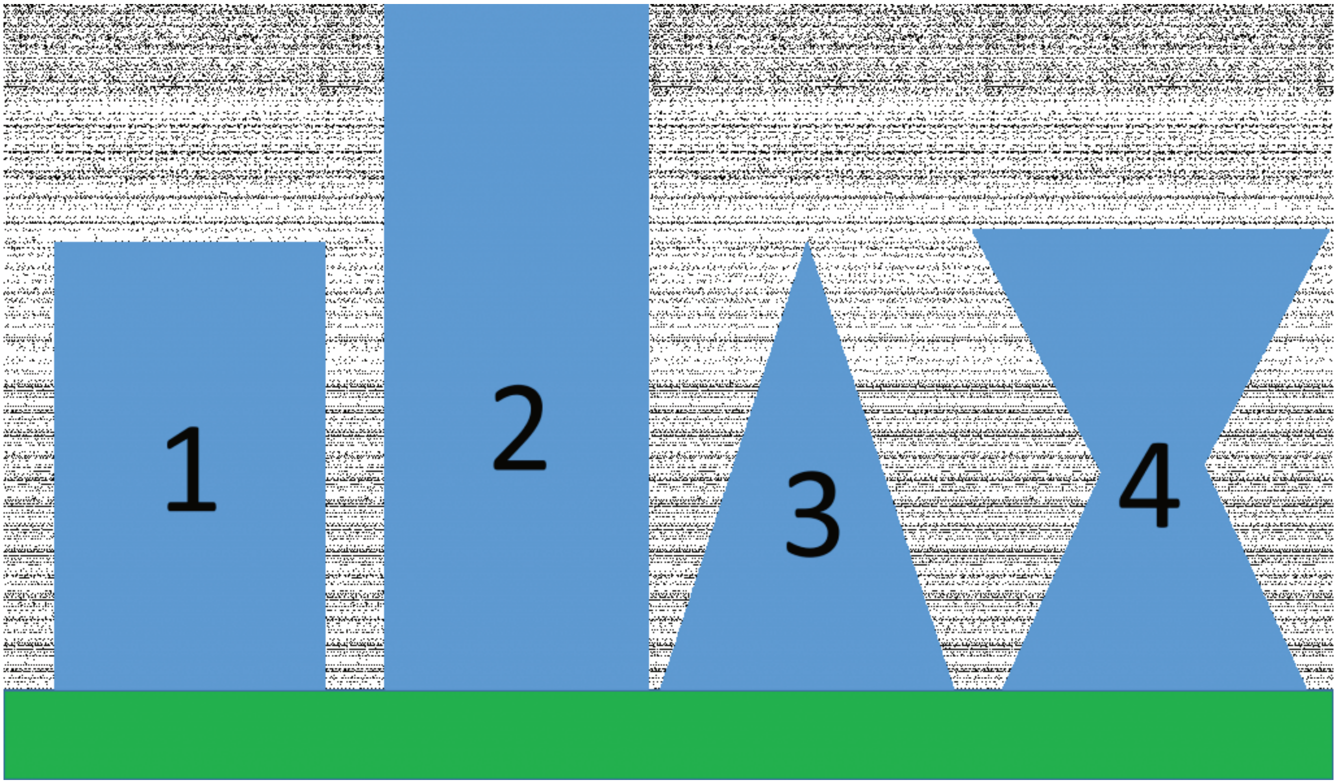
Outcome 3

7) State which type of equilibrium is exhibited by each structure below: stable, unstable, or metastable.



Four structures in static equilibrium

8) Rank the structures below in order of increasing stability. All structures are solid and made of a single material type.



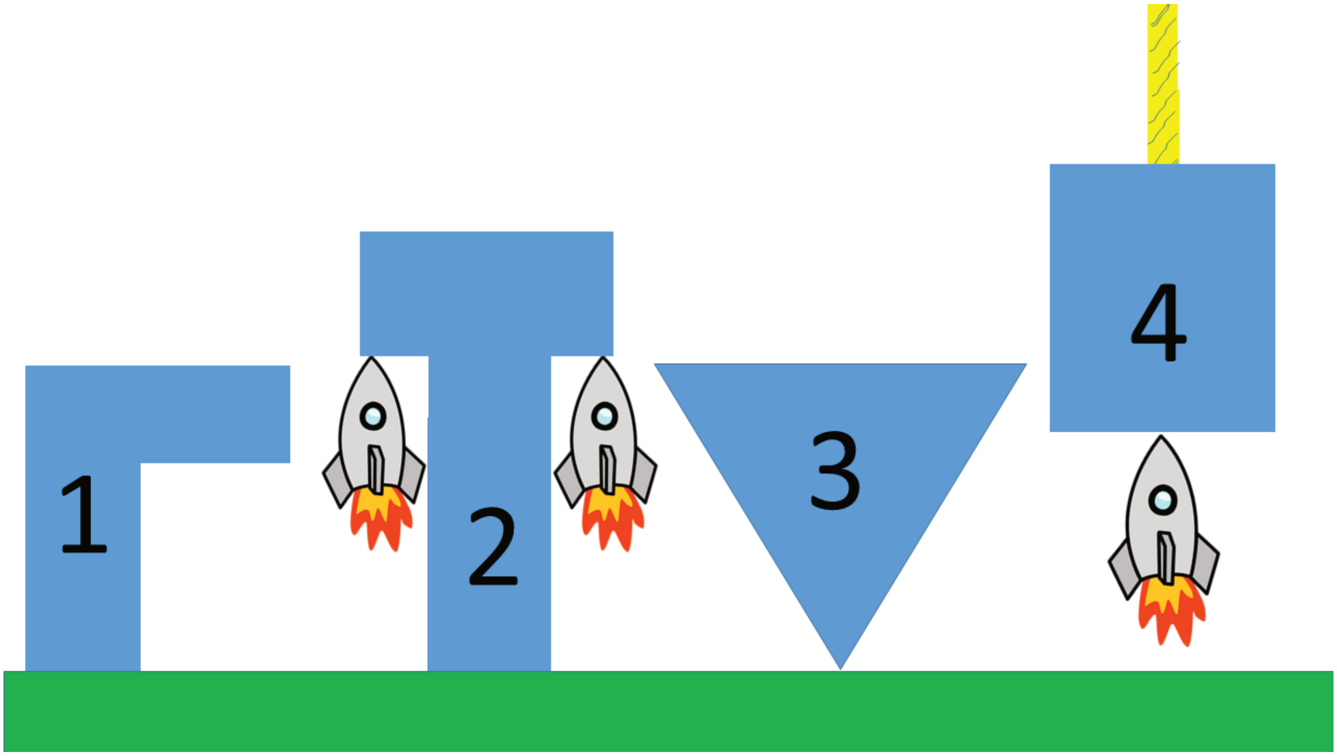
Four structures in metastable equilibrium.

Outcome 4

9) A car with a weight of 10,000 **N** is sitting on concrete with the parking brake on.
a) What is the net force on the car?
b) What is the net torque on the car?

10) What is the normal force from the concrete on the car from exercise 9?
b) What is the maximum horizontal force that can be applied before the car begins to skid? List your sources for the friction coefficient.
c) After the car begins to skid, how much force is required to keep it moving at constant speed, despite kinetic friction?
d) If you apply only 120 **N** of horizontal force to the stationary car, what is the static frictional force at that time?

11) Each structure in the following image is at rest.
a) What do you know about the net force on each block?
b) Structure #1 weighs 5000 **N**. What is the normal force on the structure?
c) Structure # 2 weighs 5000 **N**. Each rocket is capable of pushing with 1000 **N** of force. What is the normal force on the structure from the ground?
d) Structure # 4 weighs 5000 **N**. The rocket is capable of pushing with 1000 **N** of force. What is the tension force provided by the rope?



Four structures of equal weight. The second structure has rockets pushing up on it and the fourth structure is hanging from a rope. Rocket images from http://wpclipart.com are in the Public Domain.

PART VI.

UNIT 6: STRENGTH AND ELASTICITY OF THE BODY

Learner Objectives

1. Identify classes of levers and explain advantages and disadvantages of each classes in terms of mechanical advantage and range of motion.[2]
2. Apply lever and static equilibrium concepts to solve for forces and calculate mechanical advantage in scenarios involving levers. [3]
3. Identify and define the features of a stress-strain curve, including stress, strain, elastic region, elastic modulus, elastic limit, plastic region, ultimate strength, and fracture/rupture.[2]
4. Apply the Hooke's Law along with the definitions of stress, strain, and elastic modulus to calculate the deformations of structures. [3]

CHAPTER 48.

BODY LEVERS

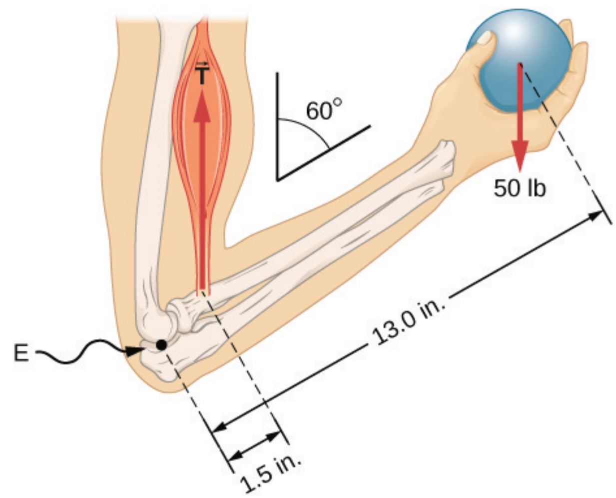
LEVERAGE

Moving patients is a routine part of Jolene's work as a MED floor RN, but in reality there is nothing routine about the biomechanics of lifting and transferring patients. In fact, "disabling back injury and back pain affect 38% of nursing staff" and healthcare makes up the majority of positions in the top ten ranking for risk of back injury, primarily due to moving patients. Spinal load measurements indicated that all of the routine and familiar patient handling tasks tested placed the nurse in a high risk category, even when working with a patient that "[had a mass of] only 49.5 **kg** and was alert, oriented, and cooperative—not an average patient."[1] People are inherently awkward shapes to move, especially when the patient's bed and other medical equipment cause the nurse to adopt awkward biomechanic positions. The forces required to move people are large to begin with, and the biomechanics of the body can amplify those forces by the effects of leverage, or lack thereof. To analyze forces in the body, including the effects of leverage, we must study the properties of levers.

LEVER CLASSES

The ability of the body to both apply and withstand forces is known as strength. One component of strength is the ability apply enough force to move, lift or hold an object with weight, also known as a load. A lever is a rigid object used to make it easier to move a large load a short distance or a small load a large distance. There are three classes of levers, and all three classes are present in the body[2][3]. For example, the forearm is a 3rd class lever because the biceps pulls on the forearm between the joint (fulcrum) and the ball (load). To see these body levers in action check out this short video animation identifying levers in the body.

1. "Nurses and Preventable Back Injuries" by Deborah X Brown, RN, BSN, American Journal of Critical Care
2. "Lever of a Human Body" by Alexandra, The Physics Corner
3. "Kinetic Anatomy With Web Resource-3rd Edition " by Robert Behnke , Human Kinetics

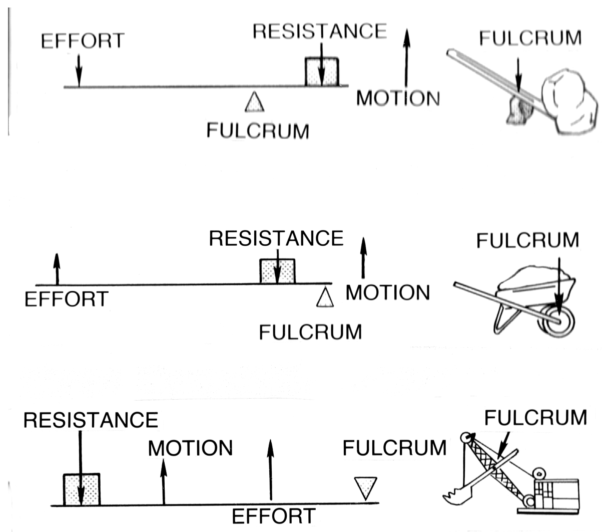


The elbow joint flexed to form a 60° angle between the upper arm and forearm while the hand holds a 50 ***lb*** *ball . Image Credit: Openstax University Physics*

[4]

Using the standard terminology of levers, the forearm is the lever, the biceps tension is the effort, the elbow joint is the fulcrum, and the ball weight is the resistance. When the resistance is caused by the weight of an object we call it the load. The lever classes are identified by the relative location of the resistance, fulcrum and effort. First class levers have the fulcrum in the middle, between the load and resistance. Second class levers have resistance in the middle. Third class levers have the effort in the middle.

4. OpenStax University Physics, University Physics Volume 1. OpenStax CNX. Jul 11, 2018 http://cnx.org/contents/d50f6e32-0fda-46ef-a362-9bd36ca7c97d@10.18.

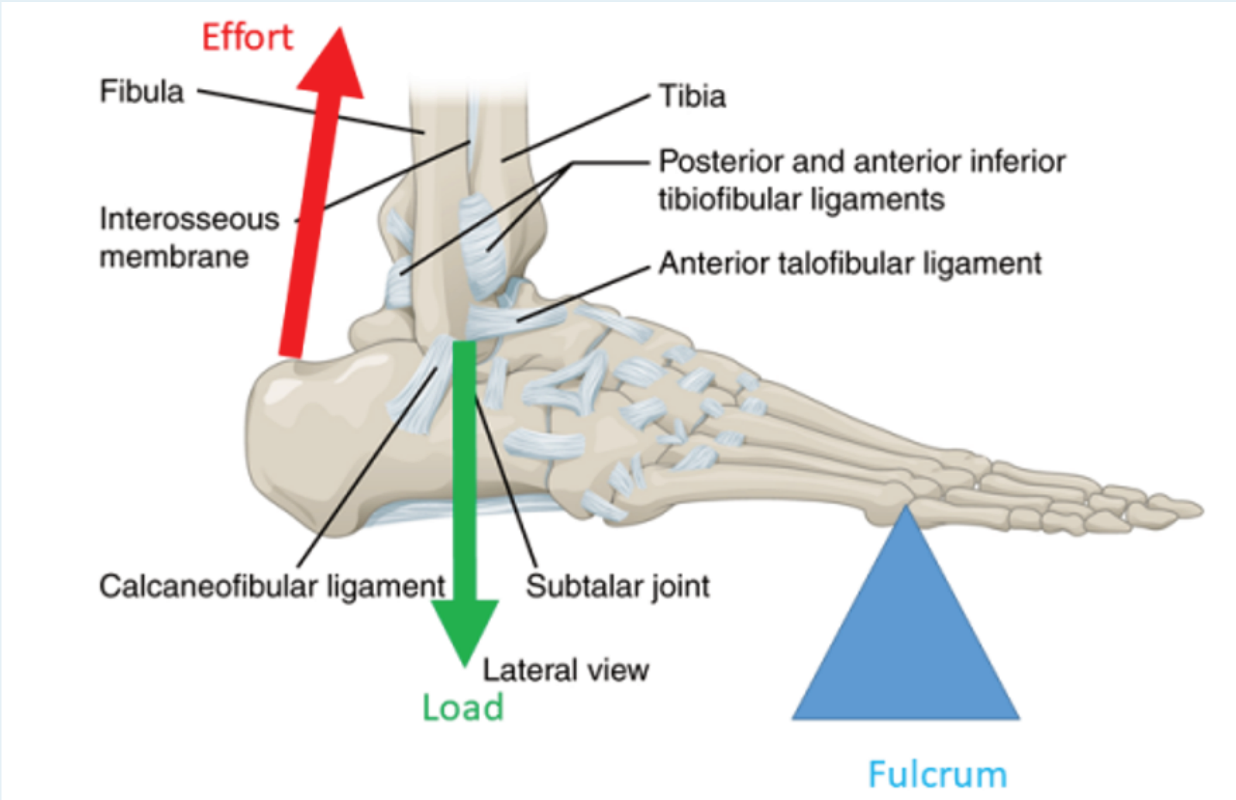


First (top), second(middle), and third(bottom) class levers and real-world examples of each. Image Credit: Pearson Scott Foresman

5

5. "Lever" by Pearson Scott Foresman , Wikimedia Commons is in the Public Domain

Reinforcement Activity



The foot acting as a lever arm with calf muscle supplying an upward effort, the weight of the body acting as downward load, and the ball of the foot acting as the fulcrum. Image adapted from OpenStax Anatomy and Physiology

[6]

STATIC EQUILIBRIUM IN LEVERS

For all levers the effort and resistance (load) are actually just forces that are creating torques because

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6. OpenStax, Anatomy & Physiology. OpenStax CNX. Jun 25, 2018 http://cnx.org/contents/14fb4ad7-39a1-4eee-ab6e-3ef2482e3e22@10.1.

they are trying to rotate the lever. In order to move or hold a load the torque created by the effort must be large enough to balance the torque caused by the load. Remembering that torque depends on the distance that the force is applied from the pivot, the effort needed to balance the resistance must depend on the distances of the effort and resistance from the pivot. These distances are known as the effort arm and resistance arm (load arm). Increasing the effort arm reduces the size of the effort needed to balance the load torque. In fact, the ratio of the effort to the load is equal to the ratio of the effort arm to the load arm:

$$\frac{load}{effort} = \frac{effort\,arm}{load\,arm} \quad (1)$$

Every Day Examples: Biceps Tension

Let's calculate the biceps tension need in our initial body lever example of a holding a 50 **lb** ball in the hand. We are now ready to determine the bicep tension in our forearm problem. The effort arm was 1.5 **in** and the load arm was 13.0 **in**, so the load arm is 8.667 times longer than the effort arm.

$$\frac{13\,\cancel{in}}{1.5\,\cancel{in}} = 8.667$$

That means that the effort needs to be 8.667 times larger than the load, so for the 50 **lb** load the bicep tension would need to be 433 **lbs**! That may seem large, but we will find out that such forces are common in the tissues of the body!

**Adjusting Significant Figures*

Finally, we should make sure our answer has the correct significant figures. The weight of the ball in the example is not written in scientific notation, so it's not really clear if the zeros are placeholders or if they are significant. Let's assume the values were not measured, but were chosen hypothetically, in which case they are exact numbers like in a definition and don't affect the significant figures. The forearm length measurement includes zeros behind the decimal that would be unnecessary for a definition, so they suggest a level of precision in a measurement. We used those values in multiplication and division so we should round the answer to only two significant figures, because 1.5 **in** only has two (13.0 **in** has three). In that case we round our bicep tension to 430 **lbs**, which we can also write in scientific notation: $4.3 \times 10^2\ \mathbf{lbs}$.

**Neglecting the Forearm Weight*

Note: We ignored the weight of the forearm in our analysis. If we wanted to include the effect of the weight of the forearm in our example problem we could look up a typical forearm weight and also look up where the center of gravity of the forearm is located and include that load and resistance arm. Instead let's take this opportunity to practice making *justified* assumptions. We know that forearms typically weigh only a few pounds, but the ball weight is 50 **lbs**, so the forearm weight is about an order of magnitude (10x) smaller than the ball weight[7]. Also, the center of gravity of the forearm is located closer to the pivot than the weight, so it would cause significantly less torque. Therefore, it was reasonable to assume the forearm weight was negligible for our purposes.

MECHANICAL ADVANTAGE

The ratio of load to effort is known as the mechanical advantage (*MA*). For example if you used a

7. "Weight, Volume, and Center of Mass of Segments of the Human Body" by Charles E. Clauster, et al, National Technical Information Service, U.S. Department of Commerce

second class lever (like a wheelbarrow) to move 200 **lbs** of dirt by lifting with only 50 **lbs** of effort, the mechanical advantage would be four. The mechanical advantage is equal to the ratio of the effort arm to resistance arm.

$$MA = \frac{load}{effort} = \frac{effort\,arm}{load\,arm} \quad (2)$$

Reinforcement Activity

RANGE OF MOTION

We normally think of levers as helping us to use less effort to hold or move large loads, so our results for the forearm example might seem odd because we had to use a larger effort than the load. The bicep attaches close to the elbow so the effort arm is much shorter than the load arm and the mechanical advantage is less than one. That means the force provided by the bicep has to be much larger than the weight of the ball. That seems like a mechanical disadvantage, so how is that helpful? If we look at how far the weight moved compared to how far the bicep contracted when lifting the weight from a horizontal position we see that the purpose of the forearm lever is to increase range of motion rather than decrease effort required.

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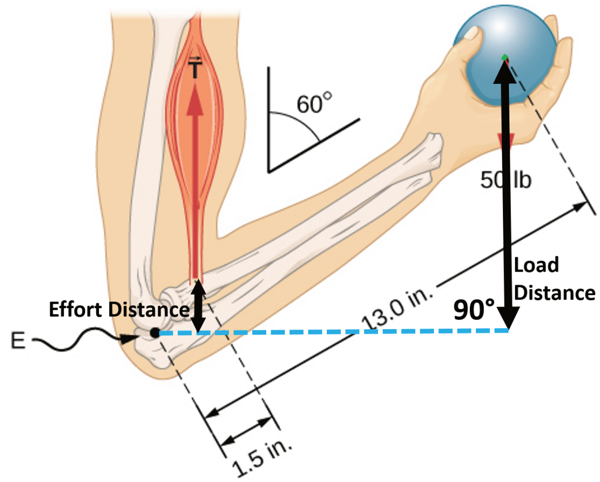

Diagram showing the difference in distance covered by the contracting bicep and the weight in the hand when moving the forearm from horizontal.Image Adapted from Openstax University Physics

Looking at the similar triangles in a stick diagram of the forearm we can see that the ratio of the distances moved by the effort and load must be the same as the ratio of effort arm to resistance arm. That means increasing the effort arm in order to decrease the size of the effort required will also decrease the range of motion of the load *by the same factor*. It's interesting to note that while moving the attachment point of the bicep 20% closer to the hand would make you 20% stronger, you would then be able to move your hand over a 20% smaller range.

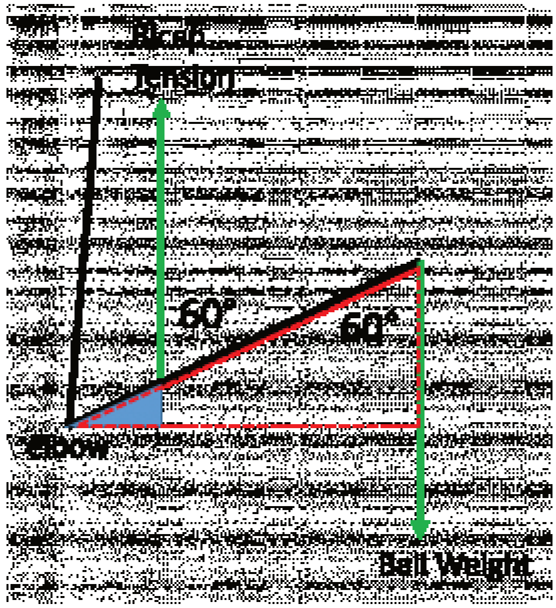

Diagram of the forearm as a lever, showing the similar triangles formed by parts of the forearm as it moves from 90 degrees to 60 degrees from horizontal. The hypotenuse (long side) of the smaller blue triangle is the effort arm and the hypotenuse of the larger dashed red triangle is the load arm. The vertical sides of the triangles are the distances moved by the effort (blue) and the load (dashed red).

Reinforcement Exercises

For third class levers the load is always farther from the fulcrum than the effort, so they will always increase range of motion, but that means they will always increase the amount of effort required by the same factor. Even when the effort is larger than the load as for third class levers, we can still calculate a mechanical advantage, but it will come out to be less than one.

Second class levers always have the load farther from the pivot than the effort, so they will always allow a smaller effort to move a larger load, giving a mechanical advantage greater than one.

First class levers can either provide mechanical advantage or increase range of motion, depending

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on if the effort arm or load arm is longer, so they can have mechanical advantages of greater, or less, than one.

A lever cannot provide mechanical advantage and increase range of motion at the same time, so each type of lever has advantages and disadvantages:

Comparison of Advantages and Disadvantages of Lever Classes

Lever Class	Advantage	Disadvantage
3rd	**Range of Motion** The load moves farther than the effort. (*Short bicep contraction moves the hand far*)	**Effort Required** Requires larger effort to hold smaller load. (*Bicep tension greater than weight in hand*)
2nd	**Effort Required** Smaller effort will move larger load. (*One calf muscle can lift entire body weight*)	**Range of Motion** The load moves a shorter distance than the effort. (*Calf muscle contracts farther than the distance that the heel comes off the floor*)
1st (effort closer to pivot)	**Range of Motion** The load moves farther than the effort. (*Head moves farther up/down than neck muscles contract*)	**Effort Required** Requires larger effort to hold smaller load.
1st (load closer to pivot)	**Effort Required** Smaller effort will move larger load.	**Range of Motion** The load moves shorter distance than the effort.

Reinforcement Activity

Check out the following lever simulation explore how force and distance from fulcrum each affect the equilibrium of the lever. This simulation includes the effects of friction, so you can see how kinetic friction in the joint (pivot) works to stop motion and static friction contributes to maintaining static equilibrium by resisting a start of motion.

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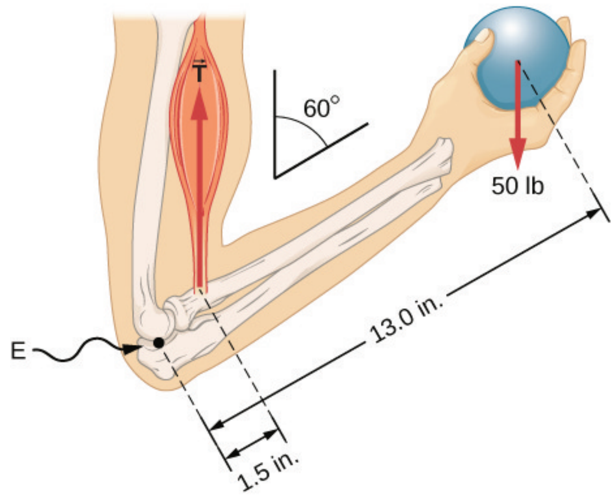
CHAPTER 49.

FORCES IN THE ELBOW JOINT

In the previous chapter we found the biceps tension force in our example problem to be 430 **lbs**! You may have noticed that when we found the biceps tension we completely ignored the forces acting at the elbow joint. We were allowed to do this because those forces cause no torque. *Forces acting on the fulcrum of a lever don't cause the lever to rotate.* Just because the forces on the elbow don't cause rotation, that doesn't mean they aren't important. Those forces can certainly damage the joint if they get too large. Let's try to find out how big those forces are for our example problem.



*The elbow joint flexed to form a 60° angle between the upper arm and forearm while the hand holds a 50 **lb** ball . Image Credit: Openstax University Physics*

[1]

The forearm is holding still and not moving so it must be in static equilibrium and all the vertical forces must be canceling out. If the vertical forces didn't cancel out the forearm would begin to move up or down. We already know that the weight of the ball is 50 **lbs** downward and the bicep tension is 433 **lbs** upward. The weight cancels 50 **lbs** worth of the muscle tension, leaving behind a remaining

1. OpenStax University Physics, University Physics Volume 1. OpenStax CNX. Jul 11, 2018 http://cnx.org/contents/d50f6e32-0fda-46ef-a362-9bd36ca7c97d@10.18.

483 **lbs** of upward force. The forearm is in static equilibrium, so the vertical force on the end of the forearm at the elbow must cancel out this 483 **lbs** upward force, meaning that the vertical force on the elbow end of the forearm is 483 **lbs** downward. This force comes from the upper arm bone (humerus) pushing down on the end of the forearm bones (radius and ulna). Adjusting our significant figures, we should report this force as 480 **lbs**.

Reinforcement Exercises

Draw a free body diagram of the elbow showing the forces from the ball weight, the bicep tension, and the upper arm pushing on the forearm. The values for all of these forces are given in the previous paragraph.

HORIZONTAL ELBOW FORCES

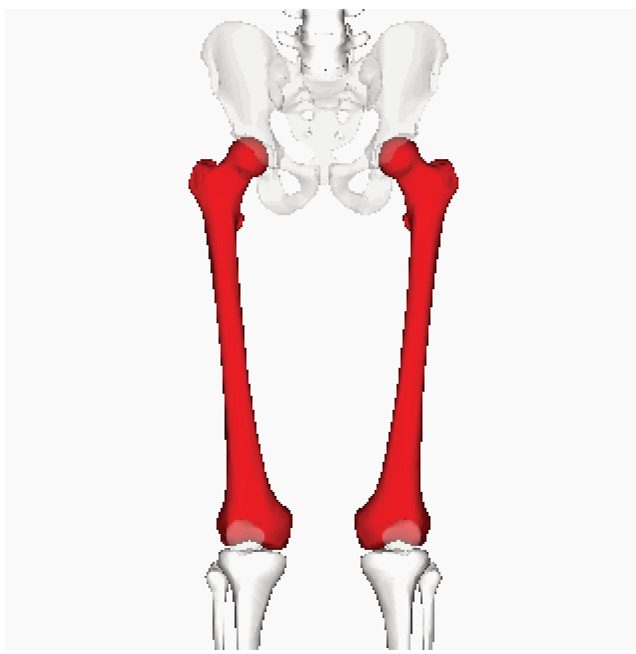
The horizontal forces must all cancel out because the forearm is in static equilibrium, but there are no horizontal forces in our example to begin with, so that's it. We're finished analyzing the forces on the forearm while holding a 50 **lb** ball!

CHAPTER 50.

ULTIMATE STRENGTH OF THE HUMAN FEMUR

COMPRESSING THE FEMUR

Opposite to tension forces, compression forces are provided by a material in response to being compressed rather than stretched. The resistance of materials to deformation is what causes the normal force (support force) that we introduced in the unit on balance. For example, the femur is compressed while supporting the upper body weight of a person.



The Human Femur. Image Credit: Anatomography via Wikimedia Commons

[1]

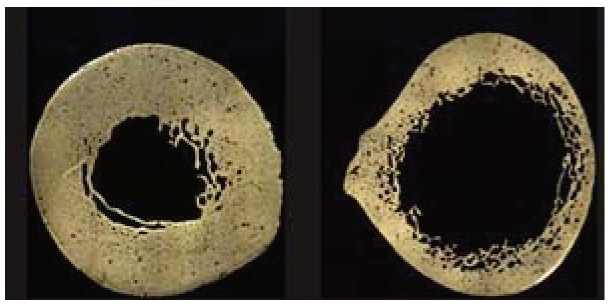
"In human anatomy, the femur (thigh bone) is the longest and largest bone. Along with the temporal bone of the skull, it is one of the two strongest bones in the body. The average adult male femur is 48 **cm** (18.9 **in**) in length and 2.34 **cm** (0.92 **in**) in diameter and can support up to 30 times the weight of an adult."[2]The average weight among adult males in the United States is 196 **lbs** (872 **N**)[3].

1. By Anatomography [CC BY-SA 2.1 jp (https://creativecommons.org/licenses/by-sa/2.1/jp/deed.en)], via Wikimedia Commons

According to the statement that the femur can support 30x body weight, the adult male femur can support roughly 6,000 **lbs** of compressive force! Such high forces are rarely generated by the body under its own power, thus motor vehicle collisions are the number one cause of femur fractures[4].

STRESS

The size of object affects how they deform in response to applied compression and tension forces. For example, the maximum compression or tension forces that a bone can support depends on the size of the bone. More specifically, the more area available for the force to be spread out over, the more force the bone can support. That means the maximum forces bones, (and other objects) can handle are proportional to the cross-sectional area of the bone that is perpendicular (90°) to the direction of the force. For example, the force that the femur can support vertically along its length depends on the area of its horizontal cross-sectional area which is roughly circular and somewhat hollow (bone marrow fills the center space).



These cross sections show the midshaft of the femur of an 84-year-old female with advanced osteoporosis (right), compared to a healthy femur of a 17-year-old female (left). Image Credit: Smithsonian National Museum of Natural History

[5]

Larger bones and tendons can support more force, so in order to analyze the behavior of the bone material itself we would need to divide the force applied to by the cross-sectional area (A_x). The resulting quantity is known as the stress (σ) on the material. Stress has units of force per area so the SI units are ($\mathbf{N/m^2}$) which are also known as Pascals. Units of pounds per square inch (**PSI**, $\mathbf{lbs/in^2}$) are common in the U.S.

(1) $$stress = \sigma = \frac{F}{A_x}$$

2. "Femur" by Orthapaedics One
3. "Body Measurement" by FastStats, U.S. Centers for Disease Control is in the Public Domain
4. "Femur Shaft Fractures" by OrthoInfo, American Academy of Orthopaedic Surgeons
5. "Effects of a Chronic Condition: Osteoporosis" by Written in Bone, Smithsonian National Museum of Natural History

Reinforcement Exercises

ULTIMATE STRENGTH OF THE FEMUR

The maximum stress that bone, or any other material, can experience before the material begins fracture or rupture is called the ultimate strength. Notice that material strength is defined in terms of stress, not force, so that we are analyzing the material itself, without including the effect of *how much* material is present. For some materials the ultimate strength is different when the stress is acting to crush the material (compression) versus when the forces are acting to stretch the material under tension, so we often refer to ultimate tensile strength or ultimate compressive strength. For example, the ultimate compressive strength for human femur bone is measured to be 205 **MPa** (205 Million Pascals) under compression along its length. The ultimate tensile strength of femur bone under tension along its length is 135 **MPa.**[6] Along with bone, concrete and chalk are other examples of materials with different compressive and tensile ultimate strengths.

Reinforcement activity

Everyday Example: Femur Ultimate Strength

Let's check to see if the measured values for compressive ultimate strength agree with the claim that the human femur can support 30x the adult body weight, or roughly 6,000 **lbs**

First let's to convert the claimed 6,000 **lbs** force to Newtons and work in SI units.

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6. "Elastic anisotropy of bone" by Rod Lakes , College of Engineering, University of Wisconson

$$6,000\,\mathbf{lbs} = 6,000\,\cancel{\mathbf{lbs}}\left(\frac{4.45\,\mathbf{N}}{1\,\cancel{\mathbf{lb}}}\right) = 26,166\mathbf{N}.$$

An approximate minimum cross-sectional area of the femur is $3.2 \times 10^{-4}\,\mathbf{m^2}$. (**See the bottom of this example if you are interested in learning how we approximated this value*). We divide the compressive force by the cross-sectional area to find the compressive stress on the bone.

$$Stress = \frac{force}{area} = \frac{26,166\,\mathbf{N}}{3.2 \times 10^{-4}\,\mathbf{m^2}} = 80,000,000\,\mathbf{Pa} = 80\,\mathbf{MPa}$$

Our approximate value for the ultimate strength of bone that would be required to support 30x body weight was 80 **MPa**, which is actually less than the measured value of 205 **MPa**, so the claim that the femur can support 30x body weight seems reasonable.

**This is how we approximated the femur cross-sectional area, skip this if you aren't interested:*

First we divide the 2.34 **cm** femur diameter quoted earlier by two to find the femur radius, then we convert to standard units of meters.

$$r = \frac{2.34\,\cancel{\mathbf{cm}}}{2}\left(\frac{1\,\mathbf{m}}{100\,\cancel{\mathbf{cm}}}\right) = 0.0117\,\mathbf{m} = 1.17 \times 10^{-2}$$

Using the equation for the area of a circle we calculate the total area of the femur to be:

$$A_{out} = \pi r^2 = \pi\,(0.0117\,\mathbf{m})^2 = 0.00043\,\mathbf{m^2} = 4.3 \times 10^{-4}\,\mathbf{m^2}$$

Finally we have to subtract off the area of the hollow middle part to get the net bone area. We used a ruler on the above picture of the femur cross-sections to see that the inner radius is roughly half of the outer radius, or $5.85 \times 10^{-3}\mathbf{m}$ so we calculate the missing inner area:

$$A_{in} = \pi r^2 = \pi\left(5.85 \times 10^{-3}\,\mathbf{m}\right)^2 = 1.1 \times 10^{-4}\,\mathbf{m^2}$$

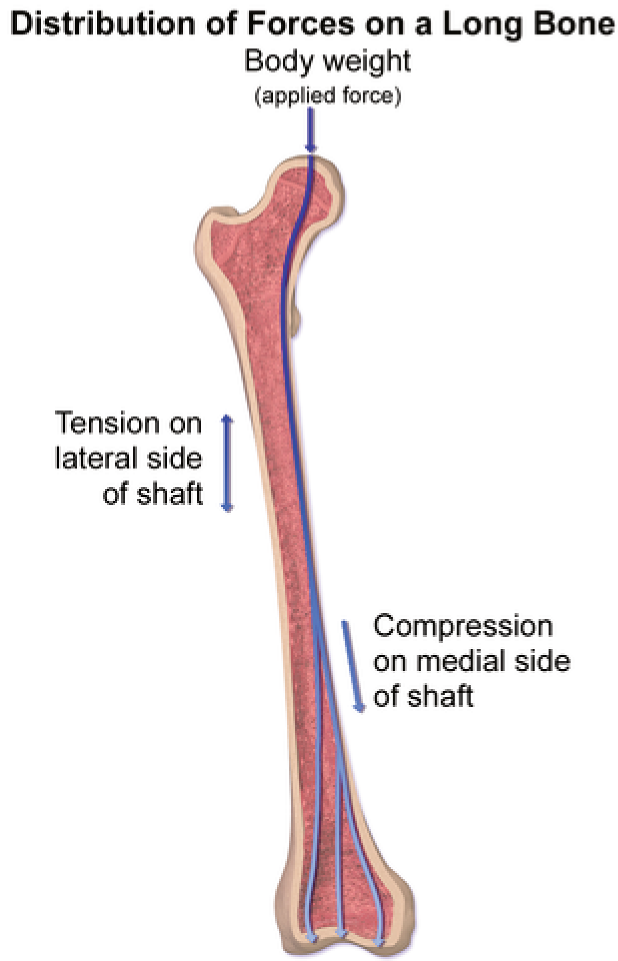
And subtract off the inner area from the total:

$$A_x = 4.3 \times 10^{-4}\,\mathbf{m^2} - 1.1 \times 10^{-4}\,\mathbf{m^2} = 3.2 \times 10^{-4}\,\mathbf{m^2}$$

TRANSVERSE ULTIMATE STRENGTH

So far we have discussed ultimate strengths along the long axis of the femur, known as the longitudinal direction. Some materials, such as bone and wood, have different ultimate strengths along different axes. The ultimate compressive strength for bone along the short axis (transverse direction) is 131 **MPa**, or about 36% less than the 205 **MPa** longitudinal value. Materials that have different properties along different axes are known as anisotropic. Materials that behave the same in all directions are called isotropic.

An interesting fact to finish up this chapter: when a person stands the femur actually experiences compressive and tensile stresses on different sides of the bone. This occurs because the structure of the hip socket applies the load of the body weight off to the side rather than directly along the long axis of the bone.



Both tension and compressive stresses are applied to the Femur while standing. Image Credit: Blausen Medical via Wikimedia Commons

[7]

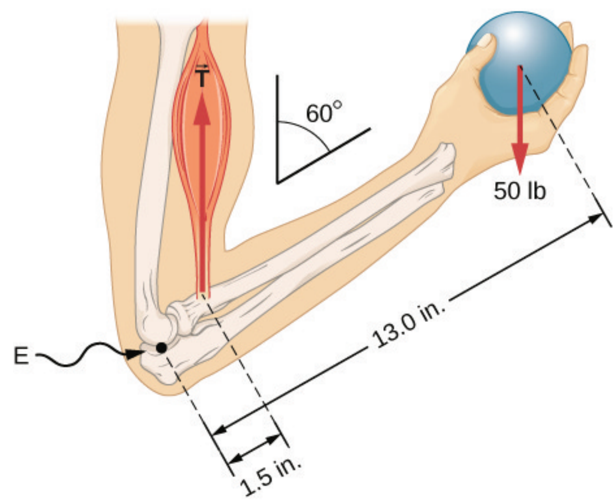
7. Blausen.com staff (2014). "Medical gallery of Blausen Medical 2014". WikiJournal of Medicine 1 (2). DOI:10.15347/wjm/2014.010. ISSN 2002-4436. [CC BY 3.0 (https://creativecommons.org/licenses/by/3.0)], from Wikimedia Commons

CHAPTER 51.

ELASTICITY OF THE BODY

BICEPS TENSION

Earlier in this unit we found that 430 **lbs** of biceps tension are required to hold a 50 **lb** weight in the hand. Tension forces are restoring forces produced in response to materials being stretched. "The biceps muscle has two tendons that attach the muscle to the shoulder and one tendon that attaches at the elbow. The tendon at the elbow is called the distal biceps tendon. It attaches to a part of the radius bone called the radial tuberosity, a small bump on the bone near your elbow joint."[1] In addition to the muscle, these tendons are under the same tension as the muscle, and are therefore being stretched. As long as the tendon is not stretched too far, it will behave elastically, meaning that it will return to its original length with no permanent deformation (damage).



The elbow joint flexed to form a 60° angle between the upper arm and forearm while the hand holds a 50 ***lb*** *ball . Image Credit: Openstax University Physics*

2

1. "Biceps Tendon Tear at the Elbow" by OrthoInfo, American Academy of Orthopedic Surgeons
2. OpenStax University Physics, University Physics Volume 1. OpenStax CNX. Jul 11, 2018 http://cnx.org/contents/d50f6e32-0fda-46ef-a362-9bd36ca7c97d@10.18.

HOOKE'S LAW

When objects, like the distal biceps tendon are only slightly stretched they will behave like springs. In that case the relationship between the tension force and stretch distance follows Hooke's Law and we often call the stretch distance the displacement, (Δx):

(1) $F = k\Delta x$

If we wanted to use Hooke's Law to calculate the stretch of the distal biceps tendon caused by the 430 **lbs** biceps tension for a particular person, we would need to know the spring constant of that person's tendon. The spring constant depends on the stiffness of a particular material, known as the Elastic Modulus, but it also depends on the size and length of the object. For example, a wider tendon will not stretch as much as a narrow one, but a longer tendon would stretch farther than a shorter one. Modeling the tendon as a spring, we can think of stretching a tendon that has twice the cross-sectional area as equivalent to stretching a two of the original springs at the same time, which would require twice the applied force to create the same displacement. We can also think of a tendon with twice the length as equivalent to stretching two of the original springs placed end-to-end. To get the same stretch as a single spring, each spring will only have to stretch half of the total distance, so that would require only half the force to create the same total displacement. Therefore, the spring constant of the tendon (or any object) is proportional to the cross-sectional area (A_x) and inversely proportional to it's length (L).

(2) $k = E\frac{A_x}{L}$

Now we can see that the size of an object affects the spring constant. Therefore the force required to achieve a particular stretch is different for objects of different size, even when they are made of the same material. Replacing the spring constant in Hooke's Law with the previous equation shows how force depends on cross-sectional area and length:

(3) $F = E\frac{A_x}{L}\Delta x$

Everyday Examples: Biceps Tendon Stretch

We can use the previous equation to calculate the stretch in the biceps distal tendon for the 430 lb tension force required to hold a 50 **lb** ball in the hand. First we need to rearrange the equation for the stretch distance by diving both sides by E, L and A_x:

(4) $\frac{F}{E}\frac{L}{A_x} = \Delta x$

A elastic modulus for tendon is 1.5 x 10^9 **N/m^2**.[3] [4]A typical length of the biceps distal tendon is 6.3 **cm** and a typical cross-sectional area is 1.5 x 10^{-5} **m^2** If we convert the length to meters (0.063 **m**) and the 430 **lb** force to Newtons (1913 **N**) we are ready to find the stretch distance using the previous equation:

(5) $\Delta x = \frac{F}{E}\frac{L}{A_x} = \frac{1913\,\mathbf{N}}{1.5\times 10^9\,\mathbf{N/m^2}}\frac{0.063\,\mathbf{m}}{3.8\times 10^{-5}\,\mathbf{m^2}} = 0.002\,\mathbf{m} = 2\mathbf{mm}$

3. "Influence of biceps brachii tendon mechanical properties on elbow flexor force steadiness in young and old males" by R. R. Smart, S. Baudry, A. Fedorov, S. L. Kuzyk and J. M. Jakobi, Wiley Online Library
4. "The distal biceps tendon: footprint and relevant clinical anatomy" by Athwal GS, Steinmann SP, Rispoli DM., U.S. National Library of Medicine, National Institutes of Health

The biceps distal tendon would stretch by an additional 2 **mm** when placed under the 430 **lb** tension.

STRAIN

Notice that the stretch in the biceps tendon that we calculated was dependent on the original length of the tendon. This makes sense because we know it's easier to stretch a long object than a short one. For example, if you tie a body-length section of 1 **cm** thick nylon rope to a pole and then pull as hard as you can the stretch will be barely noticeable. If you instead used a rope with 10x body length, you would easily notice the stretch even though both ropes were made of the same material. In order to study the properties of specific materials like tendons, independent of size, we can divide the stretch by the original length. This quantity is known as the strain (ϵ):

(6) $strain = \epsilon = \Delta x L$

Reinforcement Exercises

We need to be careful with the term strain because it has a different meaning in medical terminology where a strain is an over-stretching or tearing of muscle or tendon, which connect muscle to bones. A sprain is an over-stretching or tearing of ligaments, which connect bones together in joints.[5]

ELASTIC MODULUS

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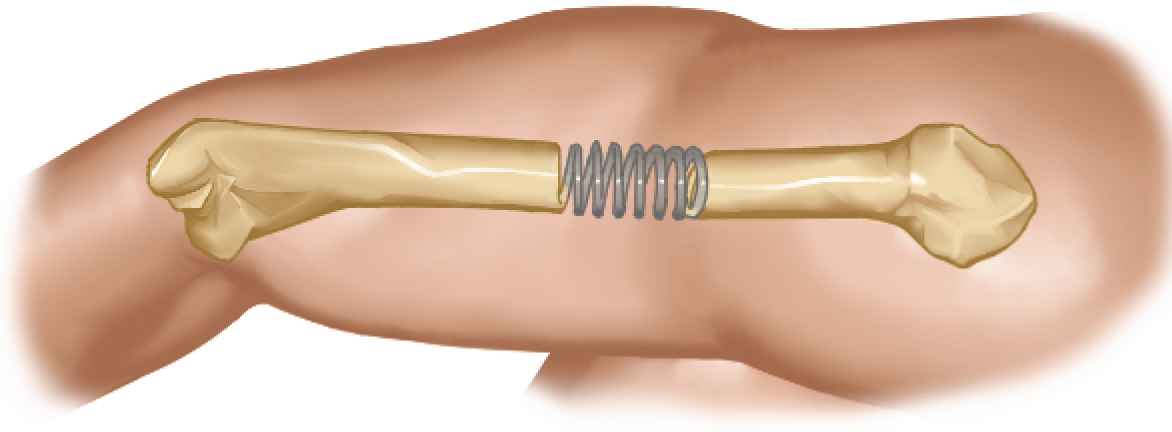
5. "Sprains and Strains" by Patient care and health information, Mayo Clinic



Artist's conception of the elastic behavior body tissues. "Armcoil" by Sasha Lynch.

Within the linear region we can model materials as springs, just like we did with the biceps distal tendon in the previous chapter. We can start by writing Hooke's Law in terms of the material elastic modulus just as we did for the bicep:

(7) $F = E\frac{A_x}{L}\Delta x$

Notice that the right hand side contains our definition of strain, so we can write

$F = E \cdot A_x \cdot strain$

If we divide both sides by cross sectional area, we will suddenly have the definition of stress on the left:

$\frac{F}{A_x} = E \cdot strain$

So we can write:

(8) $stress = E \cdot strain$

We now see that when a material is behaving like a spring, the stress will be proportional to the strain and the elastic modulus of the material will be the proportionality constant that relates the stress and strain. When an object is behaving this way, we say the stress and strain fall within the linear region of the material. To actually find the elastic modulus of a material experimentally we rearrange the equation:

(9) $E = \frac{stress}{strain}$

Then we just need to measure how much additional strain is caused by an applied stress (or *vice versa*) then divide the stress by strain to get the elastic modulus. Of course we need to be sure that the material is operating within it's linear region, so that it still acts like a spring.

Reinforcement Exercises

Just as for the ultimate strength, some materials have a different elastic modulus when the stress is applied along different axes, or even between tension and compression along the same axis. For example, the tensile elastic modulus of bone is 16 **GPa** (16 x 10^9 **Pa**) compared to 9 **GPa** under compression.[6] Check out the engineering toolbox for a massive tensile elastic modulus table. For more information on stress and strain in human tissues, including excellent diagrams, check out posted lecture notes from Professor Tony Leyland at Simon Fraser University.

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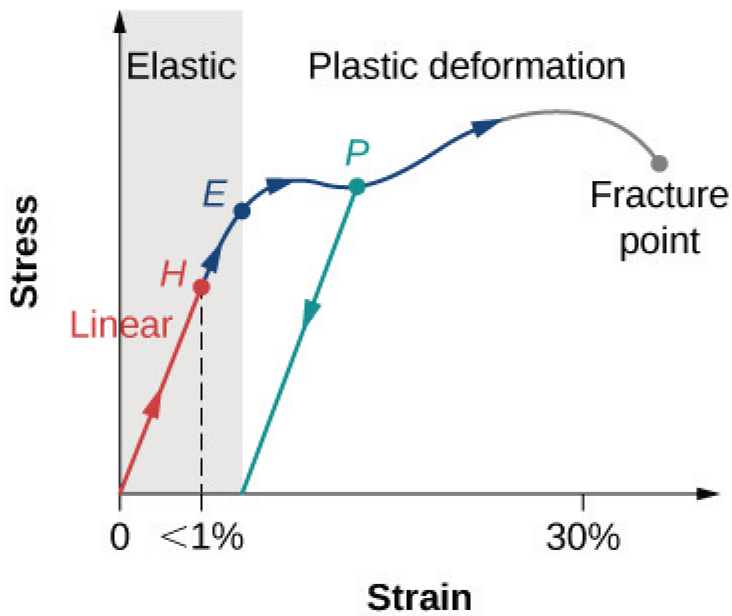
6. OpenStax, College Physics. OpenStax CNX. Aug 6, 2018 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@13.1.

CHAPTER 52.

DEFORMATION OF TISSUES

STRESS VS. STRAIN CURVES

If you apply some stress to a material and measure the resulting strain, or *vice versa*, you can create a stress vs. strain curve like the one shown below for a typical metal.



Typical stress-strain plot for a metal: The graph ends at the fracture point. The arrows show the direction of changes under an ever-increasing stress. Points H and E are the linearity and elasticity limits, respectively. The green line originating at P illustrates the metal's return to a greater than original length when the stress is removed after entering the plastic region. Image Credit: OpenStax University Physics

[1]

We see that the metal starts off with stress being proportional to strain, which means that the material is operating in its linear region. We have graphed stress on the vertical axis and strain on the

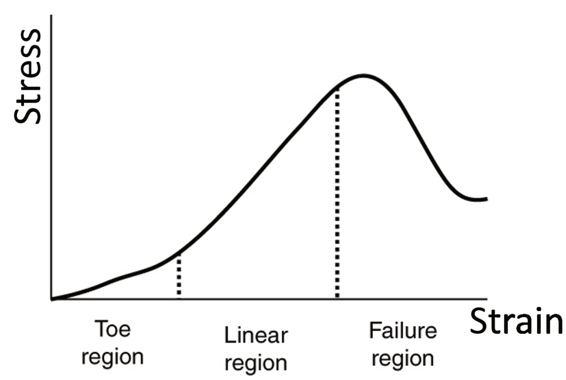
1. OpenStax University Physics, University Physics Volume 1. OpenStax CNX. Aug 2, 2018 http://cnx.org/contents/d50f6e32-0fda-46ef-a362-9bd36ca7c97d@11.1.

horizontal axis, so the value of *stress/strain* is equal to the *rise/run* of the graph. We saw in the previous chapter that within the linear region *stress/strain* is equal to the the elastic modulus and we know the *rise/run* of a graph is the slope, therefore the *elastic modulus of a material is equal to the slope of the linear portion its stress vs. curve*. Let's discuss the important features of the stress vs. strain curve:

1. The absolute highest point on the graph is the ultimate strength, indicating the onset of failure toward fracture or rupture.
2. Notice that after reaching the ultimate strength, but before full failure, the stress can actually decrease as strain increases, this is because the material is changing shape by breaking rather than stretching or compressing the distance between molecules in the material.
3. In the first part of the elastic region, the strain is proportional to the stress, this is known as the linear region. The slope of this region is the elastic modulus.
4. After the stress reaches the linearity limit (H) the slope is no longer constant, but the material still behaves elastically.
5. The elastic region ends and the plastic region begins at the yield point (E). In the plastic region, a little more stress causes a lot more strain because the material is changing shape at the molecular level. In some cases the stress can actually decrease as strain increases, because the material is changing shape by re-configuring molecules rather than just stretching or compressing the distance between molecules.
6. The green line originating at P illustrates the metal's return to non-zero strain value when the stress is removed after being stressed into the plastic region (permanent deformation).

STRESS AND STRAIN IN TENDONS

Tendons (attaching muscle to bone) and ligaments (attaching bone to bone) have somewhat unique behavior under stress. Functionally, tendons and ligaments must stretch easily at first to allow for flexibility, corresponding to the toe region of the stress-train curve shown below, but then resist significant stretching under large stress to prevent hyper-extension and dislocation injuries.



Typical stress-strain curve for mammalian tendon. Three regions are shown: (1) toe region (2) linear region, and (3) failure region. Image adapted from OpenStax College Physics.

2

2. OpenStax, College Physics. OpenStax CNX. Aug 6, 2018 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@13.1.

The structure of the tendon creates this specialized behavior. To create the toe region, a small stress causes the fibers in the tendon begin to align in the direction of the stress, or uncrimp, and the re-alignment provides additional length. Then in the linear region, the fibrils themselves will be stretched.

STRESS AND STRAIN INJURIES

Stress beyond the yield point will cause permanent deformation and stress beyond the ultimate strength will cause fracture or rupture. These occurrences in body tissues are known as injuries. For example, s*prains* occur when a ligament (connects bone to bone) is torn by a stress greater than its ultimate strength, or even just stretched beyond its elastic region. The same event occurring in a tendon (connects muscle to bone) is called known as *strain*.[3] We already know that strain has a different, but related meaning to physicists and engineers, so that discrepancy in terminology is something to watch out for.

Reinforcement Activity

A YouTube element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=777

3. "Sprains and Strains" by Patient Care and Health Information, Mayo Clinic

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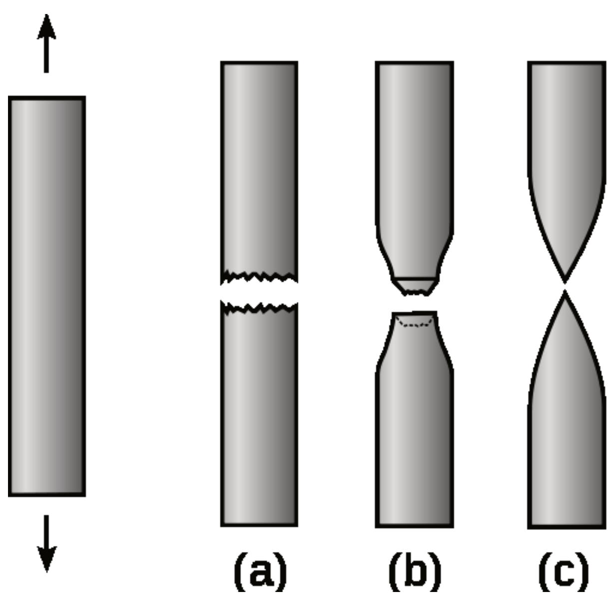
CHAPTER 53.

BRITTLE BONES

Brittle materials have a small plastic region and they begin to fail toward fracture or rupture almost immediately after being stressed beyond their elastic limit. Bone, cast iron, ceramic, and concrete are examples of brittle materials. Materials that have relatively large plastic regions under tensile stress are known as ductile. Examples of ductile materials include aluminum and copper. The following figure shows how brittle and ductile materials change shape under stress. Even the cartilage that makes up tendons and ligaments is relatively brittle because it behaves less like example (c) and more like examples (a) and (b). Luckily, those tissues have adapted to allow the deformation required for mobility by, which is the purpose of the toe region of their stress vs. strain curves.



Profile (a) is an example of the material that fractures with no plastic deformation, i.e., it is a brittle material. Profile (b) is an example of a material that fractures after very little plastic deformation. These two profiles would be classified as having low ductility. Profile (c) in contrast is a material that plastically deforms before fracture. This material has high ductility. Image Credit: Sigmund (Own work) [CC BY-SA 3.0], via Wikimedia Commons

Materials that are very malleable can undergo significant plastic deformation under compressive stress, as apposed to tensile stress. Very malleable materials can be pounded into thin sheets. Gold is the most malleable metal.[1]

Reinforcement Exercises

An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=1126

1. "Malleability and Ductility" by John A. Dutton e-Education Institute, Penn State University

CHAPTER 54.

EQUILIBRIUM TORQUE AND TENSION IN THE BICEP*

TORQUE ABOUT THE ELBOW

So far we have used lever concepts and static equilibrium to solve for the forces in our forearm example. To gain a deeper understanding of why and how the effort and load forces depend on the effort arm and load arm distances, we can make a closer study of the concepts of torque and static equilibrium. We have already decided that the weight of the ball was pulling the forearm down and trying to rotate it around the elbow joint. When a force tends to start or stop rotating an object then we say the force is causing a torque (τ) . In our example, the weight of the ball is causing a torque on the forearm with the elbow joint as the pivot. The size of a torque depends on several things, including the distance from the pivot point to the force that is causing the torque.

Reinforcement Activity

The torque caused by a force depends on the distance that force acts from the pivot point. To feel this effect for yourself, try this:

Open a door by pushing perpendicular to the door near the handle, which is far from the pivot point at the hinges.

Now apply the same force perpendicular to the door, but right next to the hinges. Does the door open as easily as before, or did you have to push with greater force to make the door rotate?

One method to account for the effect of the distance to pivot when calculating the size of a torque you can first draw the line of action of the force, which just means to extend a line from both ends of the force arrow (vector) in both directions. Next you draw the shortest line that you can from the pivot point to the line of action of the force. This shortest line and the line of action of the force will always be at 90° to each other, so the shortest line is called the *perpendicular distance* $(d_{\perp})$. The perpendicular distance is also sometimes called the lever arm or *moment arm* or torque arm. We can draw these lines for our example problem:

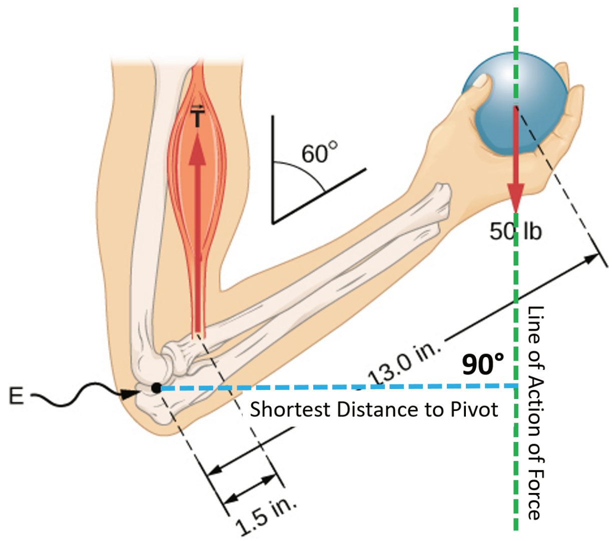


Diagram of the flexed arm showing the line of action of the gravitational force and the perpendicular distance from the pivot to the line of action. Image adapted from Openstax University Physics.

Finally, we can calculate the torque by multiplying the size of the force by the length of the lever arm ($Fd_{\perp}$) and that's it, you get the torque. In symbol form it looks like this:

(1) $torque = \tau = Fd_{\perp}$

Reinforcement Activity

STATIC EQUILIBRIUM

For an object to be in static equilibrium both the equilibrium conditions must be met. Writing these conditions on the torque and force in symbol form we have:

(2) $\tau_{\mathbf{net}} = 0$

AND

(3) $\mathbf{F}_{\mathbf{net}} = 0$

BICEP TENSION

The torques due to the bicep tension and the ball weight are trying to rotate the elbow in opposite

An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=449

directions, so if the forearm is in static equilibrium the two torques are equal in size they will cancel out and the net torque will be zero.

Looking at our equation for torque, we see that it only depends on the size of the force and the lever arm. That means that if the perpendicular distance to the bicep tension were 10x smaller than the distance to the center of the ball, the bicep tension force will have to be 10x times bigger than the weight of the ball in order to cause the same size torque and maintain rotational equilibrium. To find the bicep tension all we need to do now is determine how many times bigger the is the lever arm for the weight compared to the lever arm for the tension.

You might be thinking, *but we can't use this method, we don't know the perpendicular lengths, they aren't given, we only have the full distances from pivot to ball and pivot to bicep attachment.* Don't worry, if we draw a stick figure diagram we can see two triangles formed by the force action lines, the forearm and the perpendicular distances. The dashed (red) and solid (blue) triangles are similar triangles, which means that their respective sides have the same ratios of lengths.

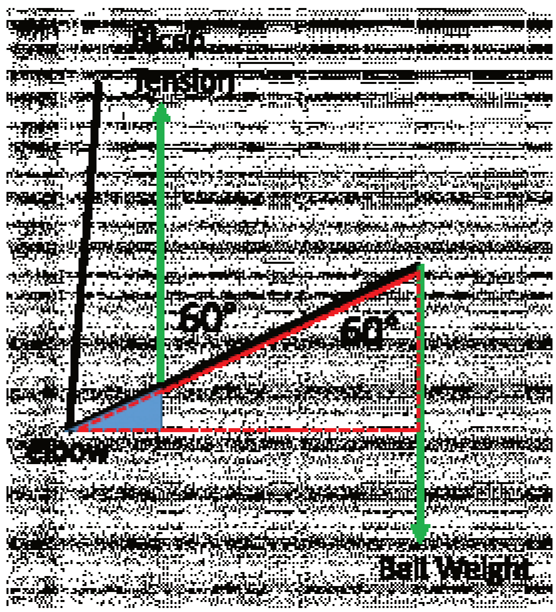


Diagram of the forearm as a lever, showing the similar triangles formed by parts of the forearm as it moves from 90 degrees to 60 degrees from horizontal. The hypotenuse (long side) of the smaller blue triangle is the effort arm and the hypotenuse of the larger dashed red triangle is the load arm. The vertical sides of the triangles are the distances moved by the effort (blue) and the load (dashed red)

The lengths of the long sides of the triangles are 13.0 **in** and 1.5 **in.** Taking the ratio (dividing 13.0 by 1.5) we find that 13.0 **in** is 8.667x longer than 1.5 **in**. The bottom side of the small (solid) triangle must also be 8.667x smaller than the bottom side of the big one (dashed). That means that the lever arm for the bicep is 8.667x smaller than for the weight and so we know the bicep tension must be 8.667x bigger than the weight of the ball to maintain rotational equilibrium.

The ball weight is 50 **lbs**, so the bicep tension must be:

$8.667 \times 50\,\mathbf{lbs} = 433\,\mathbf{lbs}$

We've done it! Our result of 433 **lbs** seems surprisingly large, but we will see that forces even larger than this are common in the muscles, joints, and tendons of the body.

SYMBOL FORM

Do you want to see everything we just did to calculate the tension in symbol form? Well, here you go:

The size of the torque due to the ball weight should be the tension multiplied by perpendicular distance to the ball:

$\tau_g = F_g \cdot d_{\perp,B}$

The size of the torque due to the bicep tension should be the tension multiplied by perpendicular distance to the bicep attachment:

$\tau_T = T \cdot d_{\perp,T}$

In order for net torque to be zero, these toques must be equal in size:

$T \cdot d_{\perp,T} = F_g \cdot d_{\perp,B}$

We want the tension, so we divide both sides by $d_{\perp,T}$:

$$T = \frac{F_g \cdot d_{\perp,B}}{d_{\perp,T}}$$

From the similar triangles we know that the ratio of perpendicular distances is the same as the ratio of the triangles' long sides:

$\mathrm{d}_{\perp,T} = \frac{13.0\,\cancel{\mathrm{in}}}{1.5\,\cancel{\mathrm{in}}} = 8.667$

Finally we find the tension:

$8.667 \times 50\,\mathbf{lbs} = 433\,\mathbf{lbs}$

CHAPTER 55.

ALTERNATIVE METHOD FOR CALCULATING TORQUE AND TENSION*

If you would rather not think about finding lever arms, you can instead calculate the size of thetorque as the size of the force multiplied by the full distance to the pivot, and by the sine of the angle between the force and that full distance. Written in equation form it looks like this:

(1) $torque = \tau = F \cdot d \cdot sin\theta$

Reinforcement Activity

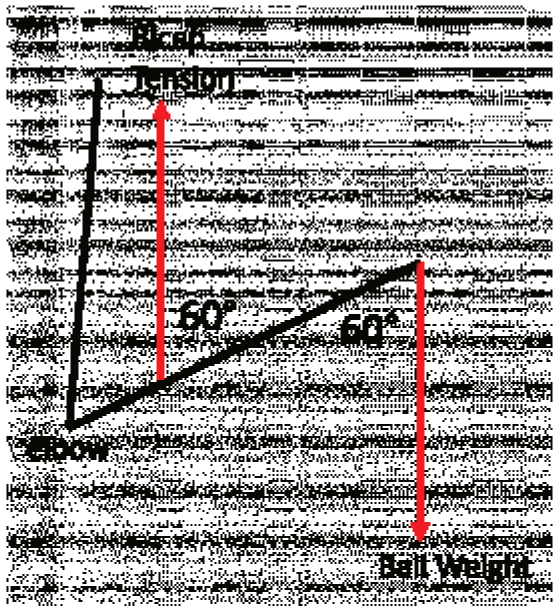
The torque caused by a force depends on the angle between the line of action of the force acts and the line from where the force is applied to the pivot point. To feel this effect for yourself, try this:

Rotate a door by pushing at 90° to the door right at the outer edge.

Now apply the same force on the door, still on the very edge, but instead of pushing in a direction 90° to the door, push along the door, straight in toward the hinges. Does the door swing as it did before?

In the second case, the angle between the force direction and the distance to the pivot was 0° (they were parallel). Use the previous equation to show that *the torque must be zero any time the line of action of the force goes straight through the rotation point (pivot).*

Now, we know the force is 50 **lbs**, the distance from the pivot to the weight is 13.0 **in** length of the forearm and from the diagram we see the angle between the weight of the ball and the forearm distance is 60° (the same as the bicep-forearm angle because they are alternate interior angles). This is easier to see if we draw a stick figure diagram:



Stick diagram of a flexed arm holding a ball showing the bicep tension and weight and the angles between the forces and the forearm.

Now we can calculate the torque due to the ball weight τ_b as:

$$\tau_b = F \cdot d \cdot sin\theta$$
$$= 50\,\mathbf{lbs} \cdot 13\,\mathbf{in} \cdot sin(60°)$$
$$= 563\,\mathbf{in} \cdot \mathbf{lbs}$$

We have calculated the torque on the forearm due to the weight of the ball. You may be used to hearing about torque in $\mathbf{ft} \cdot \mathbf{lbs}$ rather than $\mathbf{in} \cdot \mathbf{lbs}$, but we can always convert units later if we desire. For now, let's keep working on finding the muscle tension.

We already know the torque due to the weight of the ball is $563\,\mathbf{in} \cdot \mathbf{lbs}$ so we just need to make sure that the tension in the biceps is large enough to cause the same torque even though it acts closer to the pivot. The biceps muscle torque, τ_m is:

$$\tau_m = T \cdot d \cdot sin\theta$$

We just need to make this equal to the ball-weight-torque:

$$T \cdot d \cdot sin\theta = 563\,\mathbf{in} \cdot \mathbf{lbs}$$

Then we divide both sides by d and $sin\theta$ to isolate the bicep tension:

$$T = \frac{563\,\mathbf{in} \cdot \mathbf{lbs}}{d \cdot sin\theta}$$

Finally we put in our values for d and θ. Our original diagram gave us the distance as from bicep attachment to the pivot as 1.5 **in** and from our stick diagram we can see that the angle between the biceps tension and the distance is 180°-60° = 120°. We are ready to find the biceps tension value.

$$T = \frac{563\,\cancel{\mathbf{in}} \cdot \mathbf{lbs}}{1.5\,\cancel{\mathbf{in}} \cdot sin(120°)}$$

$$T = 433\,\mathbf{lbs}$$

Our result of 433 **lbs** seems surprisingly large, but we will see that forces even larger than this are common in the muscles, joints, and tendons of the body.

CHAPTER 56.

UNIT 6 REVIEW

Key Takeaways

Effort

Resistance (Load)

Fulcrum

Pivot

Lever Arm

Effort Arm

Resistance (Load) Arm

Lever Classes

Mechanical Advantage

Range of Motion

Tension

Compression

Stress

Strain

Elastic Modulus

Ultimate Strength

Linear Region

Elastic Region

Elastic Limit

Plastic Region

Yield Point

Brittle

Ductile

Learner Objectives

1. Identify classes of levers and explain advantages and disadvantages of each classes in terms of mechanical advantage and range of motion.[2]
2. Apply lever and static equilibrium concepts to solve for forces and calculate mechanical advantage in scenarios involving levers. [3]
3. Identify and define the features of a stress-strain curve, including stress, strain, elastic region, elastic modulus, elastic limit, plastic region, ultimate strength, and fracture/rupture.[2]
4. Apply the Hooke's Law along with the definitions of stress, strain, and elastic modulus to calculate the deformations of structures. [3]

CHAPTER 57.

UNIT 6 PRACTICE AND ASSESSMENT

Outcome 1

1) Consider the following items:

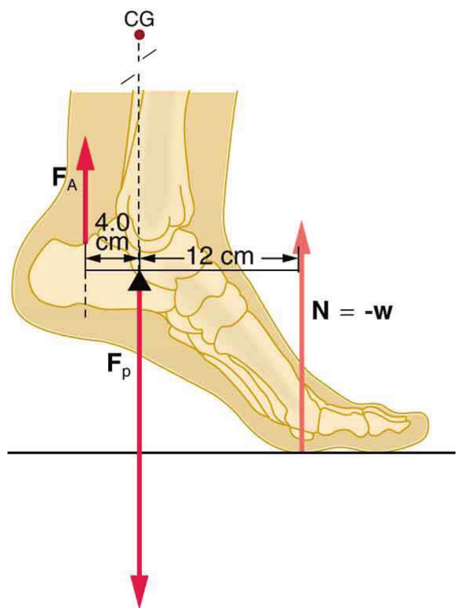
- Pliers
- Tweezers
- Shovel

(a) For each case, draw a stick figure of the tool and label the fulcrum, effort, load, effort arm, and load arm.
(b) State the class of lever for each item above.

2) For each item in the list in Exercise 1), state whether the tool is providing mechanical advantage or increasing range of motion. Explain how you know.

Outcome 2

3) When a person raises their heels off the ground, the foot acts like a lever.
(a) Typically we consider the foot as a second class lever, but if we treat the ankle bone as the fulcrum, the tension in the calf muscle as the effort, and the normal force from the floor as the resistance, what class of lever is this system?
(b) Calculate the mechanical advantage of this system.
(c) Calculate the tension applied by the calf muscles (F_A) to lift a person with weight of 637 **N**.
(d)Calculate the force in the ankle joint between the foot and the lower leg bones (F_P). [*Hint: Both the normal force from the floor and the calf tension point upward. In order for the foot to be in static equilibrium, the force of the lower leg pushing down on the foot must cancel out both of those upward forces.*]
(e) Convert your previous two answers (calf tension and force on ankle) to pounds.



The foot acting as a lever arm. Image Credit: OpenStax College Physics

[1]

4) The head and neck are also a lever system.

(a) State the class of this lever system.

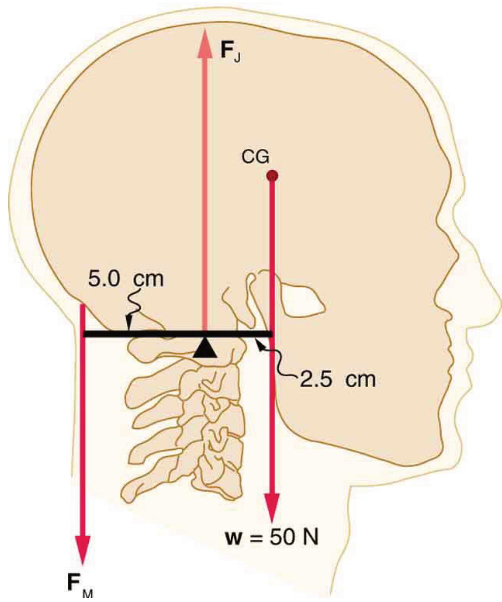
(b) Calculate the mechanical advantage of this system.

(c) Calculate the force of tension in the neck muscles (F_M) to hold the head in the position shown in the diagram.

(d) Calculate the force on the head-neck joint (F_J).

(e) Convert your previous two answers to pounds.

1. OpenStax, College Physics. OpenStax CNX. Aug 3, 2018 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@11.42

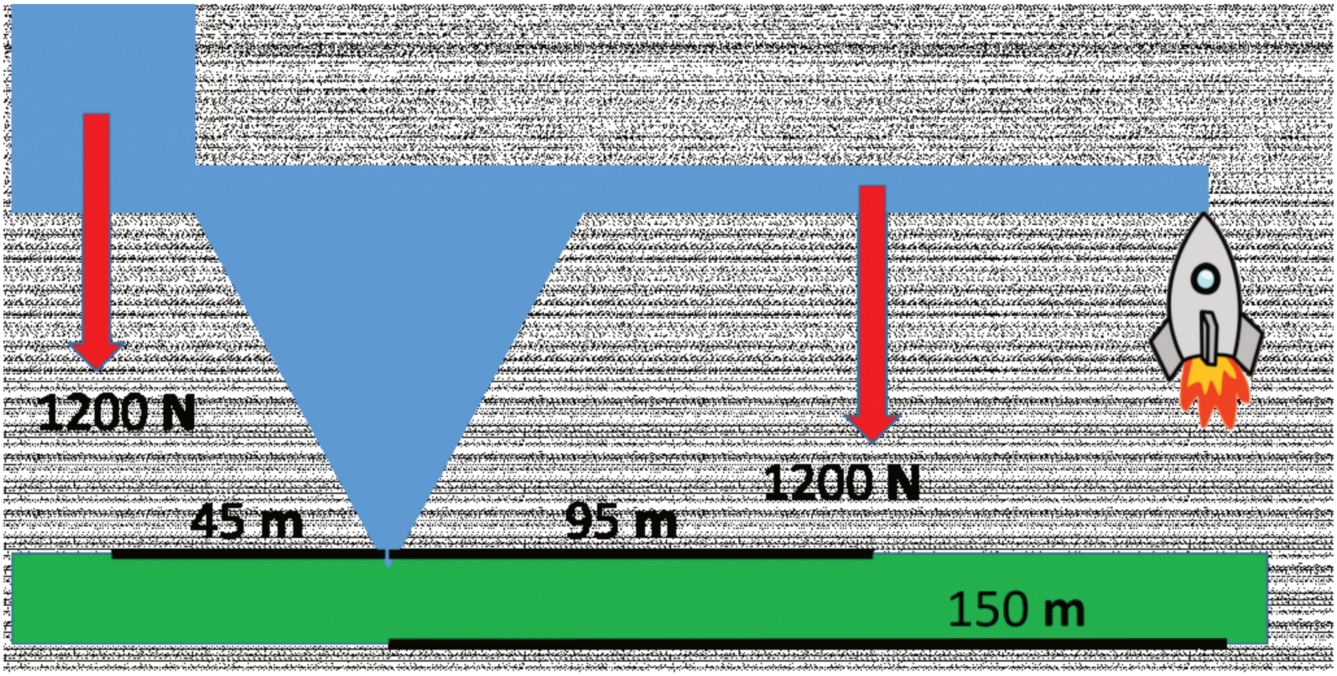


The head and neck acting as a lever system.Image Credit: OpenStax College Physics

2

5) The structure in the following image remains at rest. What do you know about the force and net torque on the structure?

2. OpenStax, College Physics. OpenStax CNX. Aug 3, 2018 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@11.42



An inverted triangular structure at rest with a block weighting one side, an arm weighting the other, and a rocket pushing up on the arm. Rocket images from http://wpclipart.com are in the Public Domain.

6) An engineer performing an inspection on the structure from the previous exercise and measures 45 **m** from beneath the center of gravity of the block to the point where the structure contacts the ground. The block weighs 1200 **N**. She then measures the distance to the beneath the center of gravity of the arm to be 95 **m**. The arm weighs 1200 **N** as well. Finally she measures the distance to beneath the rocket to be 150 **m** from the contact point. She then calculates the force being provided by the rocket.

(a) What value does the engineer get when calculating the force provided by the rocket? *[Hint: Pretend the rocket isn't there and calculate the net torque. Then find the force supplied by the rocket to balance out that net torque.]*

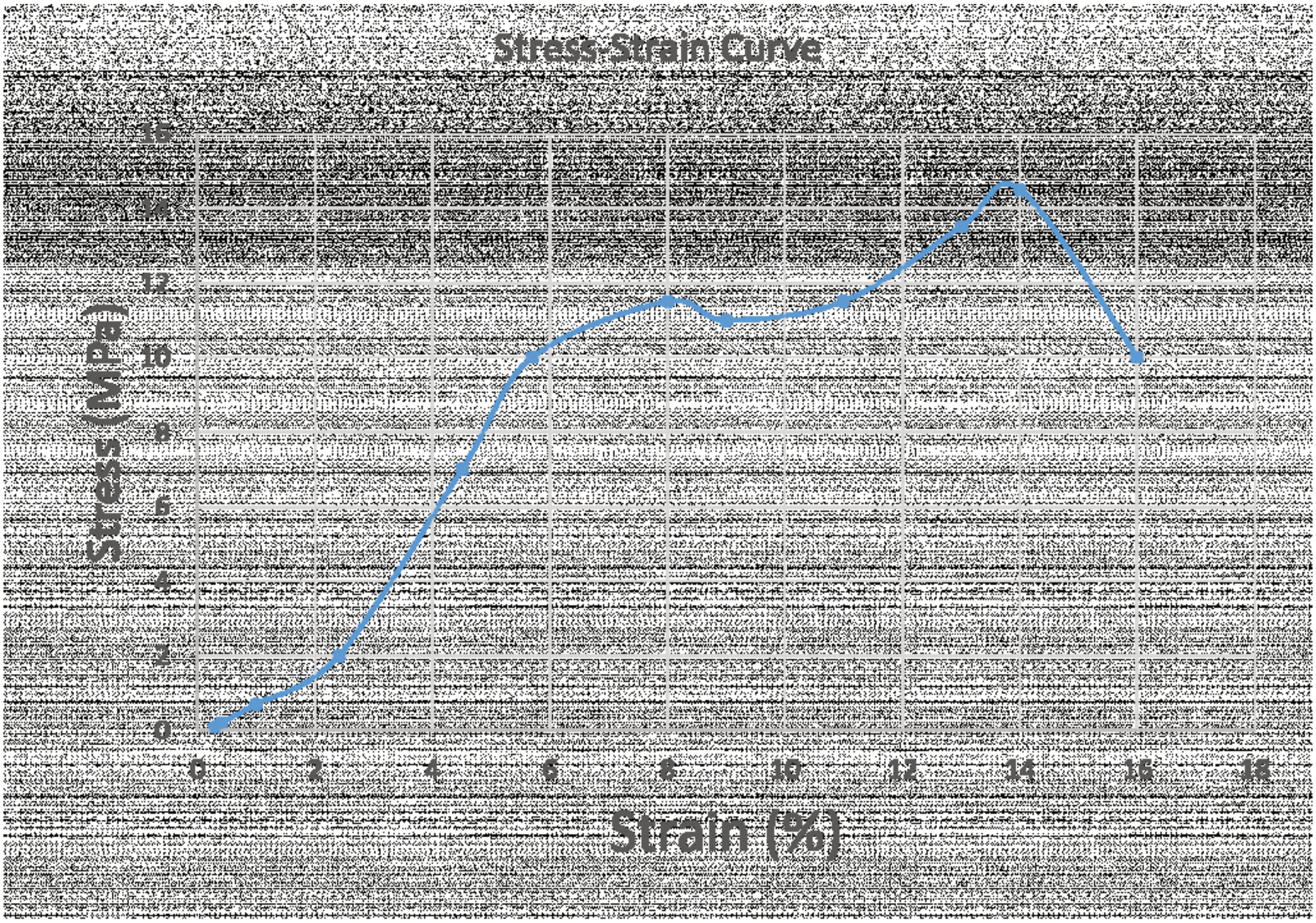
(b) The engineer then calculates the normal force on the structure from the ground, what value does she get?

Outcome 3

7) Label the following features in the stress-strain curve of a hypothetical material seen below:

- Toe region
- Elastic region
- Yield point
- Plastic Region
- Ultimate Strength

- Rupture Point
- Failure Region



Data adapted with permission from rubber band stress-strain data originally acquired by Umpqua Community College Students: Brittany Watts, Ashlie DeHart, Hanna Wicks and Juan Martinez.

8) Use the data in the previous graph to determine the elastic modulus of the hypothetical material. Be sure to convert the strain from % stretch back to fractional stretch before doing your calculations.

Outcome 4

9) A person with a weight of 715 **N** hangs from a climbing rope 9.2 **mm** in diameter.
a) What is the cross-sectional area of the rope in $\mathbf{m^2}$?
b) What is the stress applied to the rope?

10) A particular 60 **m** climbing rope stretches by 0.15 **m** when a 715 **N** person hangs from it.
a) What is the strain in the rope?
b) What is the strain in the rope as a percentage?

11) Answer the following questions regarding the material used to create the created the stress-strain graph above.

a) How much force could be applied to a 2 **m** x 2 **m** x 10 **m** long block of this material before reaching the ultimate strength?

b) When operating in the elastic region, how much additional stress would be required to cause an additional strain of 0.01?

c) What force would cause that amount of stress you found in part b on the 2 **m** x 2 **m** block?

d) What actual length would the 10 **m** long material stretch when put under the strain of 0.01?

e) What is the effective spring constant of this 2 **m** x 2 **m** x 10 **m** long block of this material?

PART VII.

UNIT 7: THE BODY IN MOTION

Learner Objectives

1. Define position, velocity, and acceleration and explain how they are related.
2. Define free-fall acceleration and calculate the drag force on objects moving through fluids.
3. Translate motion graphs into descriptions of motion in terms of position, velocity and acceleration. Translate descriptions of motion into motion graphs.
4. Apply kinematics and Newton's Second Law of Motion to analyze and predict 1-D motion.

CHAPTER 58.

FALLING

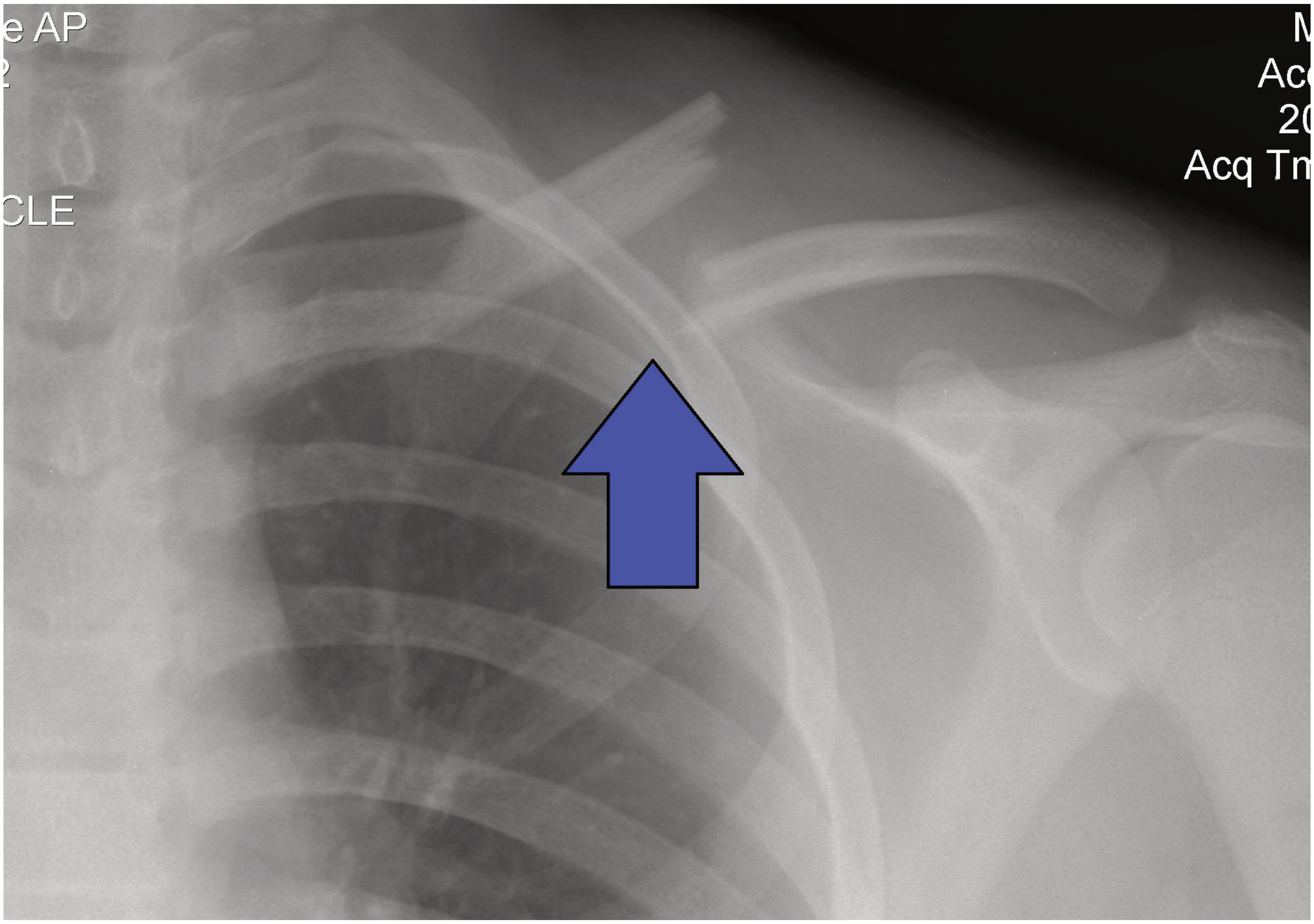
PATIENT FALLS

In the previous unit on the Strength and Elasticity we learned that lifting and holding heavy objects places quite large force (and resulting stress) on the body, so moving patients puts Jolene at risk for injury. Jolene must assume that risk because even those forces are small compared to forces experienced when impacting a hard surface during a fall. Therefore, patient falls must be avoided.

- "Falls with serious injury are consistently among the Top 10 sentinel events reported to The Joint Commission's Sentinel Event database […] with the majority of these falls occurring in hospitals.
- Every year in the United States, hundreds of thousands of patients fall in hospitals, with 30-50 percent resulting in injury.
- Injured patients require additional treatment and sometimes prolonged hospital stays that increase medical costs by an average of $14,000."

[1]

1. "Preventing falls and fall-related injuries in health care facilities" by Sentinel Event Alert, The Joint Commission



X-Ray image showing a fractured clavicle (collar bone). Clavicle fractures are a one of the most common injuries resulting from falls. This particular fracture occurred during a car accident. of Image Credit: Clavicle Fracture Left uploaded by Majorkev via Wikimedia Commons

[2]

Impacts due to falls are not the only source of large forces. In fact, any situation involving a rapid change in motion will produce relatively large forces. These include car accidents, collisions between people, jumping, landing, and explosive body movements. As a result, medical professionals and first-responders often treat patients who experience *mechanisms of injury* (MOI) that involve rapid changes in motion as having spinal and/or internal injuries until confirmed otherwise by medical imaging or complete examination. Before we can analyze the forces associated with rapid changes in motion, we must also learn how to quantify motion itself. Falling provides an excellent place to begin the study of motion, so let's start there.

2. Majorkev at English Wikipedia [CC BY 3.0 (https://creativecommons.org/licenses/by/3.0)], via Wikimedia Commons

SKYDIVING FREE FALL

Skydivers adjust body orientation to tune fall speed and adjust their relative vertical positions. Image credit: Skydive Miami by Norcal21jg, via Wikimedia Commons

[3]

The time a skydiver spends between leaving the aircraft and opening a parachute is often called the “free fall” time. During a recreational skydive the “free fall” time is about one minute. The current record “free fall” time of about 5 minutes was set by Alan Eustace in 2014 when he fell from an altitude of more than 135,000 feet. According to the Paragon Space Development Corporation, “Eustace reached top speeds of over 800 miles per hour. He was going so fast that his body broke the sound barrier, creating a sonic boom that could be heard on the ground.” The jump broke the previous record of 127,852 feet set by Felix Baumgartner in 2012. The 2012 jump was sponsored by GoPro cameras and the video has a much higher production value than the more recent 2014 jump:

PHYSICS FREE FALL

Now that we have introduced the skydiver’s use of the term free fall, we need to recognize that physics uses the term free fall in a completely different way, so we will need to be careful to avoid confusion. In physics, and in this book, we use the term free fall to describe the motion of an object when gravity is the only force acting on the object, or any other forces are small enough compared to gravity that we can ignore them without introducing too much error. Skydivers experience significant air resistance, so they are not actually in free fall.

Reinforcement Exercises

3. "Skydive Miami" by By Norcal21jg, from Wikimedia Commons is in the Public Domain

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An interactive or media element has been excluded from this version of the text. You can view it online here:
https://openoregon.pressbooks.pub/bodyphysics/?p=1010

CHAPTER 59.

DRAG FORCES ON THE BODY

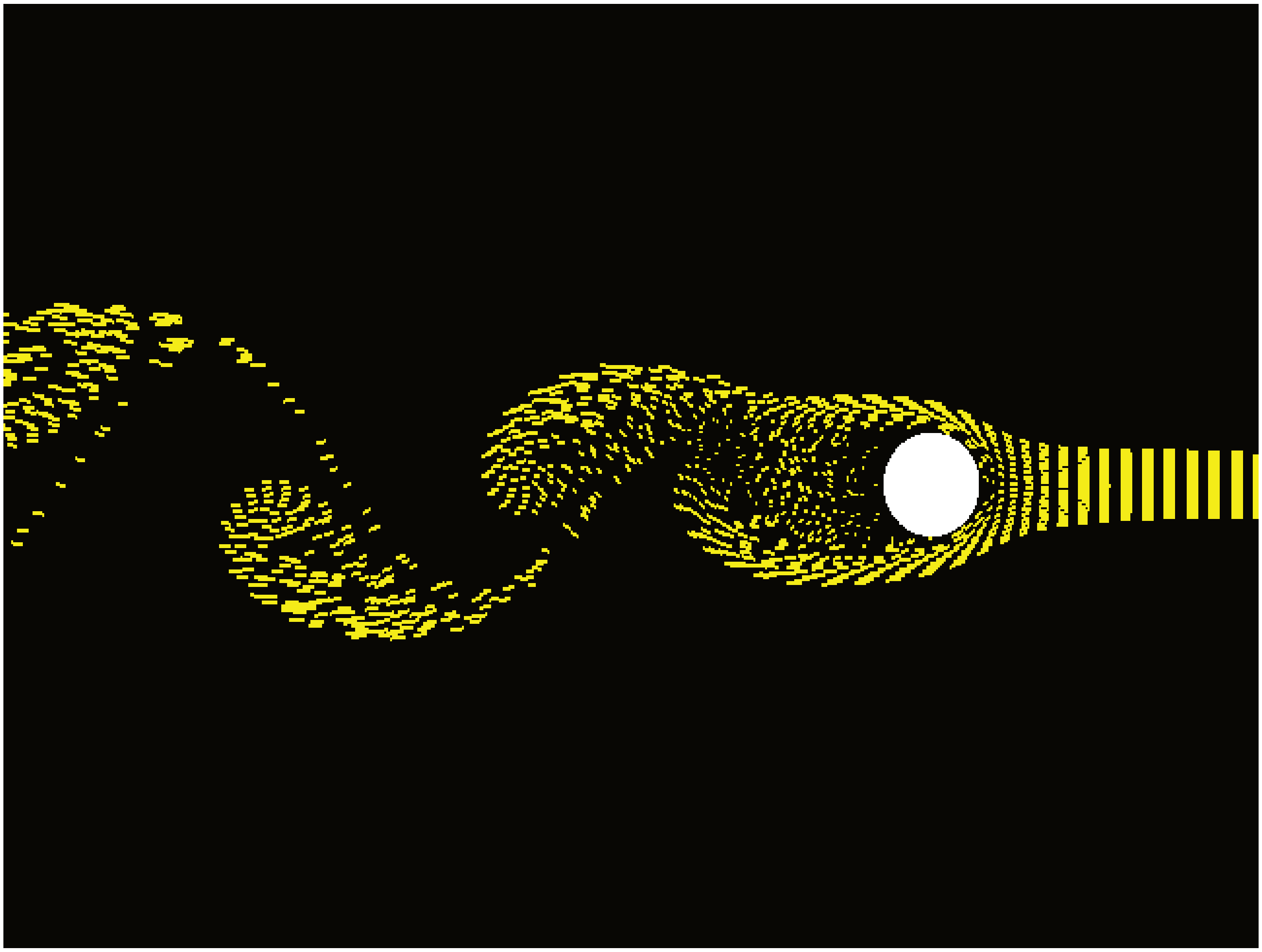
A skydiver maintains a horizontal (flat) body position with arms and legs spread, which reduces the terminal velocity and increases the fall time. Image Credit: "Gabriel Skydiving" By Gabriel Christian Brown, via Wikimedia Commons

[1]

Correct and thoughtful body orientation is an important part of skydiving because the orientation of the body affects the amount of air resistance experienced by the body. In turn, the air resistance affects the terminal speed, as we will see in the next chapter.

1. "Gabriel Skydiving" By Gabriel Christian Brown [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], from Wikimedia Commons

DRAG



Simulation of fluid flowing around a sphere. "Drag of a Sphere" by Glenn Research Center Learning Technologies Project, NASA, via GIPHY is in the Public Domain, CC0

[2]

Air resistance limits the terminal speed that a falling body can reach. Air resistance is an example of the drag force, which is force that objects feel when they move through a fluid (liquid or gas). Similar to kinetic friction, drag force is reactive because it only exists when the object is moving and it points in the opposite direction to the object's motion through the fluid. Drag force can be broken into two types: form drag and skin drag. Form drag is caused by the resistance of fluids (liquids or gases) to being pushed out of the way by an object in motion through the fluid. Form drag is similar to the normal force provided by the resistance of solids to being deformed, only the fluid actually moves instead of just deforming. Skin drag is essentially a kinetic frictional force caused by the sliding of the fluid along the surface of the object.

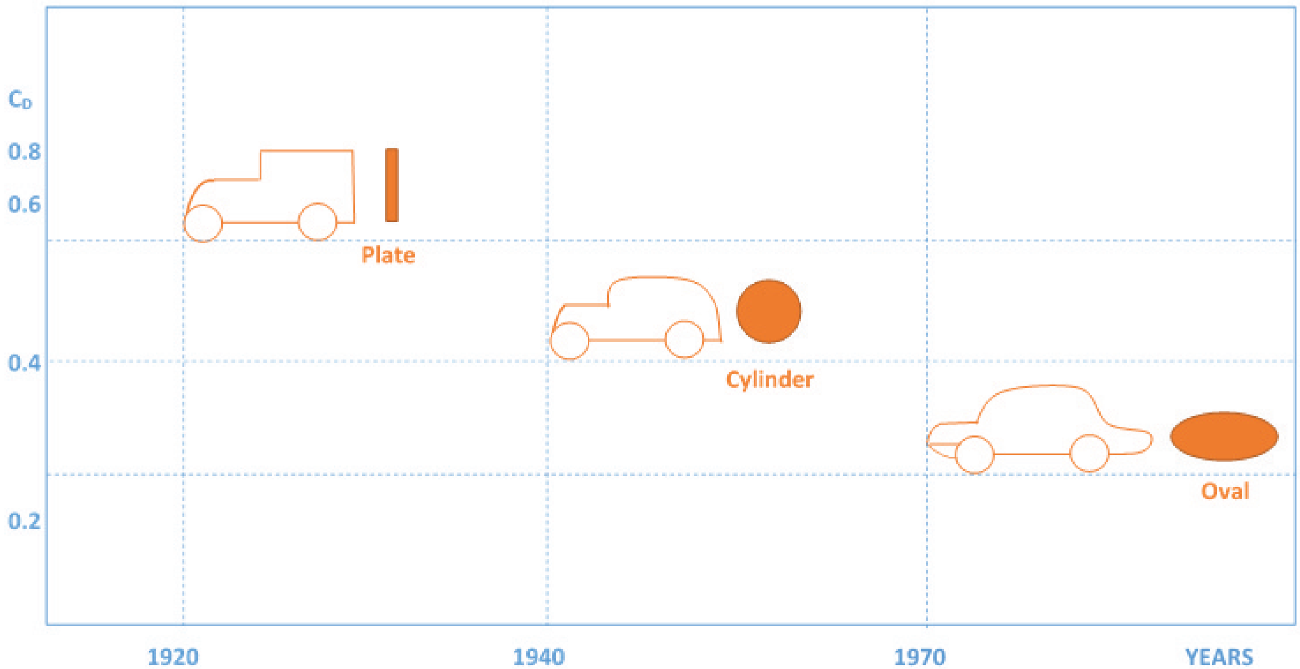
The drag force depends the density of the fluid (ϱ), the maximum cross-sectional area of the object(A_x), and the drag coefficient (C_d), which accounts for the shape of the object. Objects with a low drag coefficient are often referred to as having an aerodynamic or streamlined shape. Finally, the drag force

2. "Drag of a Sphere" by Glenn Research Center Learning Technologies Project, NASA, via GIPHY is in the Public Domain, CC0

depends on the on the speed (v) of the object through the fluid. If the fluid is not not very viscous then drag depends on v^2, but for viscous fluids the force depends just on v. In typical situations air is not very viscous so the complete formula for air resistance force is:

(1) $F_d = \frac{1}{2} C_d \rho A_x v^2$

The image below illustrates how the shape of an object, in this case a car, affects the drag coefficient. The table that follows provides drag coefficient values for a variety of objects.



Drag coefficients of cars (vertical axis on left) have changed over time (horizontal axis). Image Credit: Drag of Car by Eshaan 1992 via Wikimedia Commons

3

Drag Coefficients of Some Common Objects

Object	Drag Coefficient (*C*)
Airfoil	0.05
Toyota Camry	0.28
Ford Focus	0.32
Honda Civic	0.36
Ferrari Testarossa	0.37
Dodge Ram pickup	0.43
Sphere	0.45
Hummer H2 SUV	0.64
Skydiver (feet first)	0.70

3. Drag of Car By Eshaan 1992 [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], from Wikimedia Commons

Bicycle	0.90
Skydiver (horizontal)	1.0
Circular flat plate	1.12

4

Reinforcement Exercises

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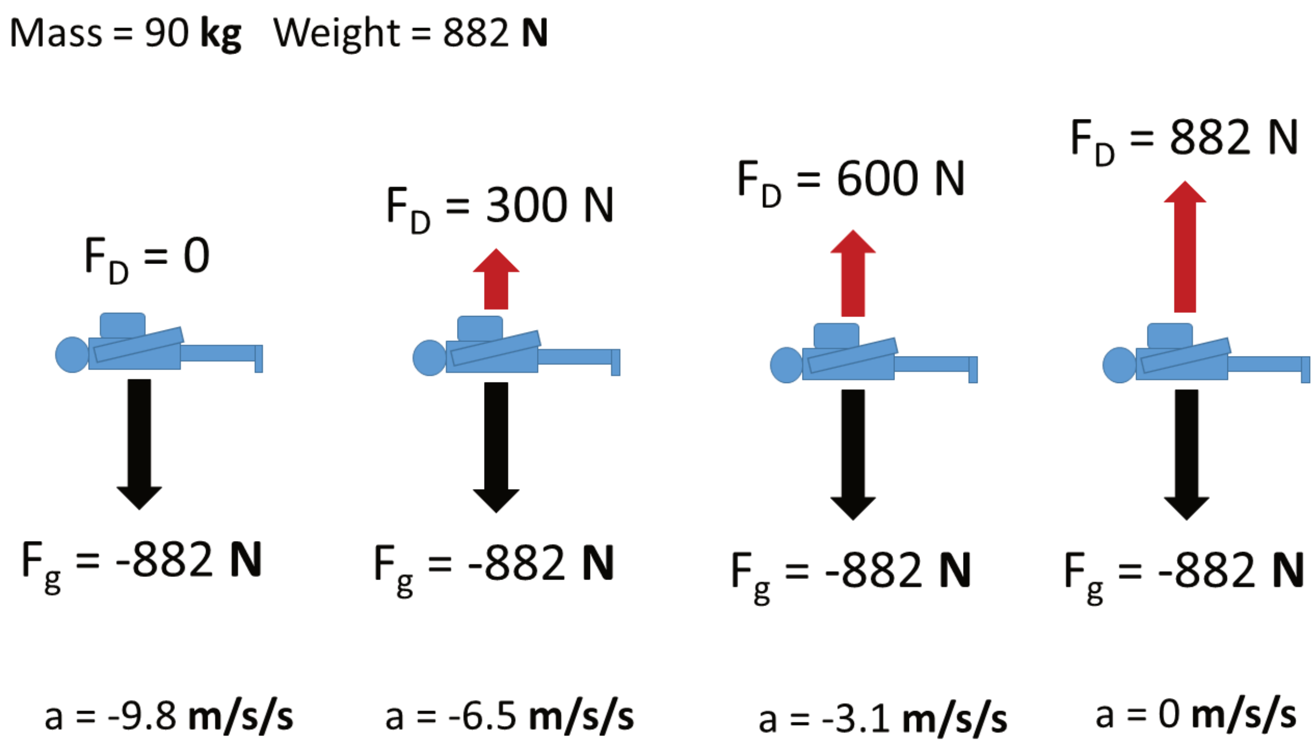
4. OpenStax, College Physics. OpenStax CNX. Jan 17, 2019 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@14.5

CHAPTER 60.

PHYSICAL MODEL FOR TERMINAL VELOCITY

After jumping, a skydiver begins gaining speed which increases the air resistance they experience. Eventually they will move fast enough that the air resistance is equal in size to their weight, but in opposite direction so they have no net force. This processes is illustrated by free body diagrams for a skydiver with 90 **kg** mass in the following image:



Free body diagrams of a person with 90 kg mass during a skydive. The initial speed is zero, so drag force is zero. As speed increases, the drag force grows, eventually cancelling out the person's weight. At that point acceleration is zero and terminal velocity is reached.

DYNAMIC EQUILIBRIUM

With a net force of zero the skydiver must be in equilibrium, but they are not in static equilibrium because they are not static (motionless). Instead they are in dynamic equilibrium, which means that they are moving, but the motion isn't changing because all the forces are still balanced (net force is zero). This concept is summarized by Newton's First Law, which tells us that an object's motion will not *change* unless it experiences a net force. Newton's first law is sometimes called the *Law of Inertia* because inertia is the name given to an object's tendency to resist changes in motion. Newton's First Law applies to objects that are not moving and to objects that are already moving. Regarding the skydiver, we are applying Newton's First Law to translational motion (back and forth, up and down), but it also holds for the effect of net torques on changes in rotational motion. Changes in motion are known as accelerations and we will learn more about how net forces cause translational accelerations in upcoming chapters.

Everyday Example: Head Injuries

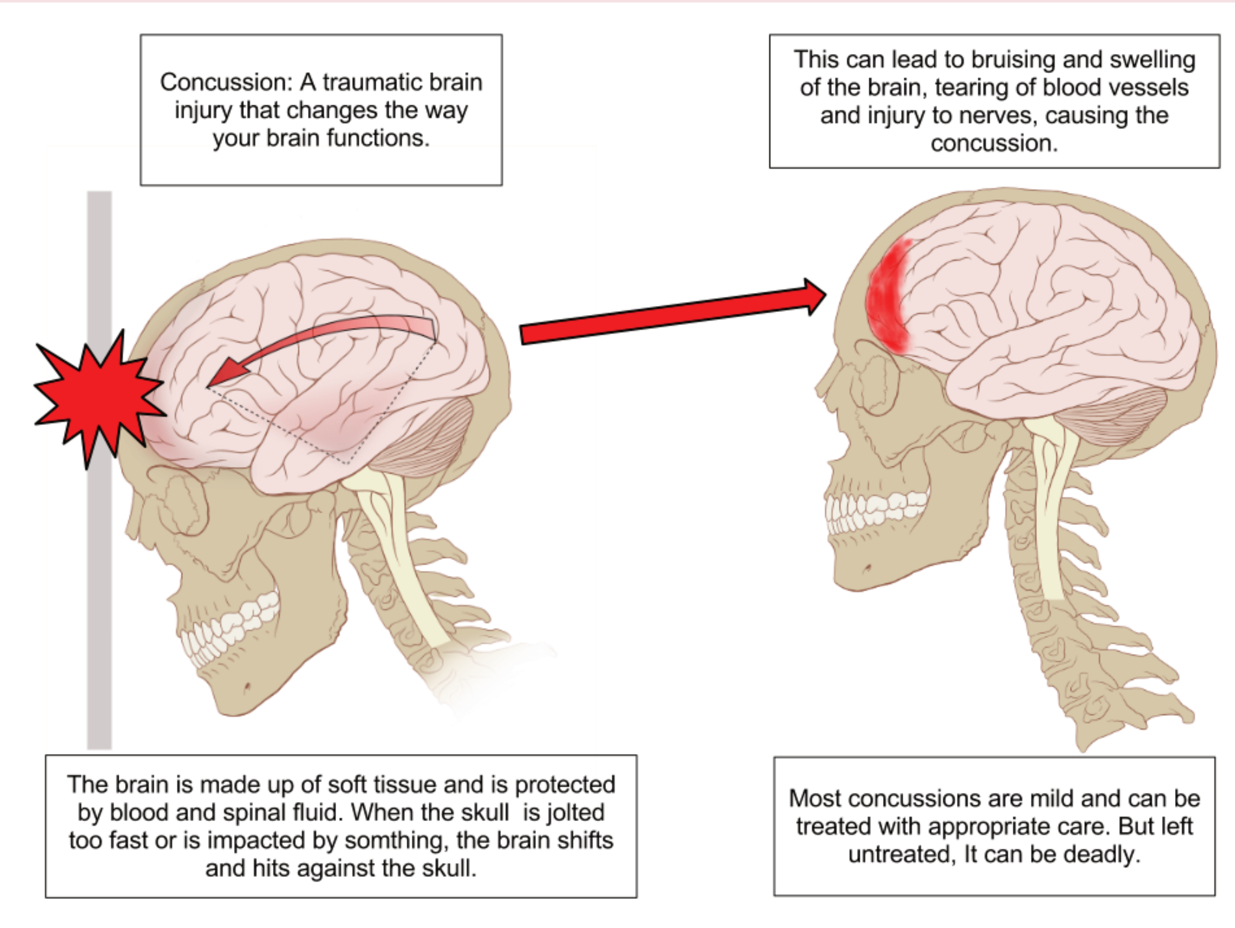


Diagram of a concussion. "Concussion Anatomy" by Max Andrews via wikimedia commons.

[1]

When the head is travelling in a certain direction with constant speed the brain and skull are moving together. If an impact causes the the motion of the skull to change suddenly, the brain tends to continue its original motion according to Newton's First Law of Motion. The resulting impact between the fragile brain and the hard skull may result in a concussion.

1. Concussion Anatomy by Max Andrews - Own work. This file was derived from: Concussion mechanics.svg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=19490504

Recent research has shown that even without the occurrence of concussions, the damage caused by sub-concussive events like this can accumulate to cause Chronic Traumatic Encephalopathy (CTE)[2].

Reinforcement Exercises

DEPENDENCE OF TERMINAL VELOCITY ON MASS

We already know from our experimental work during the Unit 3 lab that increasing mass leads to increasing terminal speed. We can now understand that this behavior occurs because greater mass leads to a greater weight and thus a greater speed required before the drag force (air resistance) is large enough to balance out the weight and dynamic equilibrium is achieved.

Everyday Example: Tandem Skydive

First-time skydivers are typically attached to an instructor (tandem skydiving). During a tandem skydive the bodies are stacked, so the shape and cross-sectional area of the object don't change much, but the mass does. As a consequence, the terminal speed for tandem diving would be high enough to noticeably reduce the fall time and possibly be dangerous. Increasing the air resistance to account for the extra mass is accomplished by deploying a small drag chute that trails behind the skydivers, as seen in the photo below.

An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=1411

2. "Concussion, microvascular injury, and early tauopathy in young athletes after impact head injury and an impact concussion mouse model" by Chad A Tagge, et. al, Brain, Oxford Academic

Tandem skydivers with a small speed-limiting drag chute trailing behind. Image Credit: Fallschirm Tandemsprung bei Jochen Schweizer By Jochen Schweizer via Wikimedia Commons

[3]

A PHYSICAL MODEL FOR TERMINAL VELOCITY

When the skydiver has reached terminal speed and remains in a state of dynamic equilibrium, we know the size of the drag force must be equal to the skydiver's weight, but in the opposite direction. This concept will allow us to determine how the skydiver's mass should affect terminal speed. We start be equating the air resistance with the weight:

$$F_d = F_g$$

Then we insert the formulas for air resistance and for weight of an object near Earth's surface. We designate the speed in the resulting equation v_T because these two forces are only equal at terminal speed.

$$\frac{1}{2}C_d\rho A_x v_T^2 = mg$$

We then need to solve the above equation for the terminal speed.

$$v_T = \sqrt{\frac{2mg}{C_d\rho A_x}} \quad (1)$$

3. By Jochen Schweizer GmbH [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], from Wikimedia Commons

Everyday Examples: Terminal Speed of the Human Body

Let's estimate the terminal speed of the human body. We start with the previous equation:

$$v_T = \sqrt{\frac{2mg}{C_d \rho A_x}}$$

We need to know the mass, drag coefficient, density of air, and cross-sectional area of the human body. Let's use the authors 80 **kg** mass and the density of air near the Earth's surface at standard pressure and temperature, $\rho = 1.2\,\mathbf{kg/m^3}$. Drag coefficient and cross sectional area depend on body orientation, so let's assume a standard skydiving posture: flat, horizontal, with arms and legs spread. In this case the drag coefficient will likely be 0.4-1.3. A reasonable value would be $C_d = 1$[4]. To approximate the cross-sectional area we can use the authors average width of 0.3 **m** and height of 1.5 **m** for an area of $A_x = 0.3\mathbf{m} \times 1.5m = 0.45\,\mathbf{m^2}$

Inserting these values into our terminal speed equation we have:

$$v_T = \sqrt{\frac{2(80\,\mathbf{kg})(9.8\,\mathbf{m/s^2})}{1(1.2\,\mathbf{kg/m^3})(0.45\,\mathbf{m^2})}} = 54\,\mathbf{m/s} = 120\mathbf{MPH}$$

Reinforcement Exercises

ACCELERATION DURING A SKYDIVE

We have now analyzed the skydive after terminal speed was reached. Prior to this point the forces of drag and weight are not equal, therefore the skydiver is not in dynamic equilibrium and speed will change over time. In order to analyze the early part of the skydive we need to quantify changes motion and learn how those changes are related to the net force. The next chapters will help us with those two goals.

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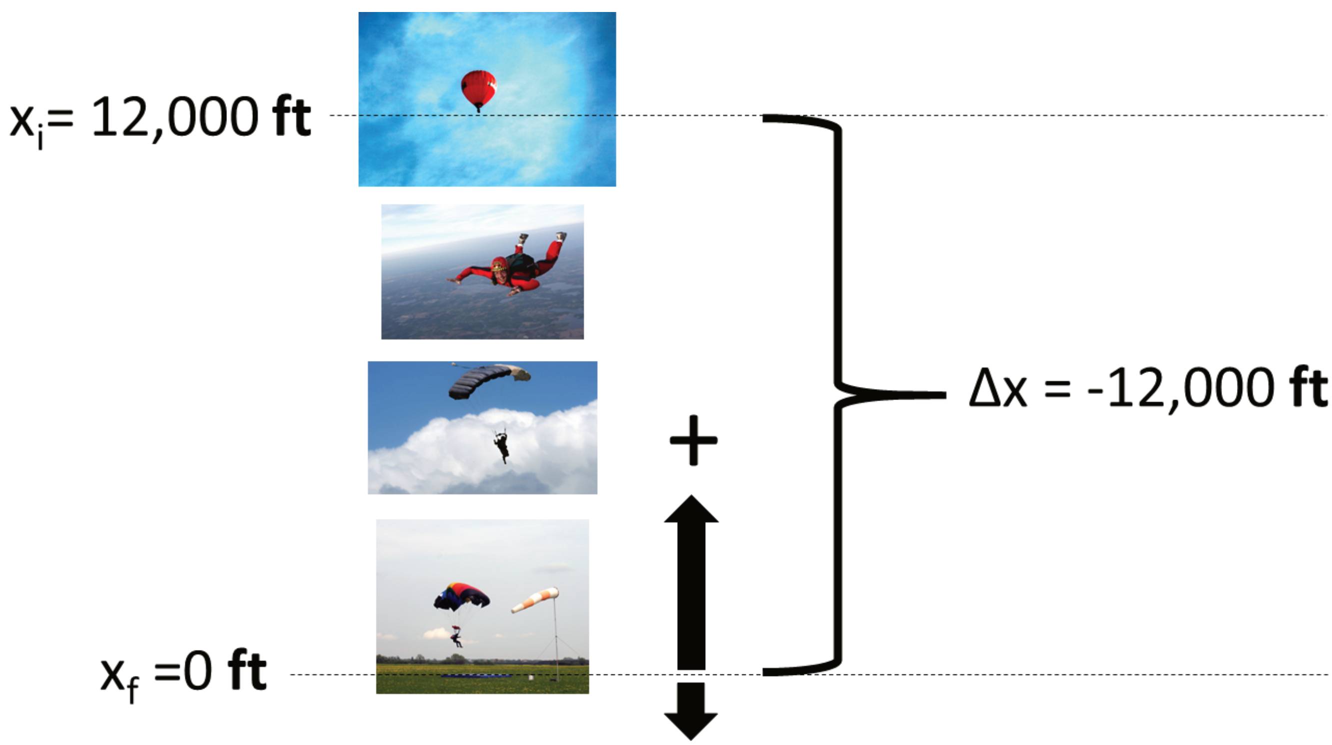
4. "Drag Coefficient" by Engineering Toolbox

CHAPTER 61.

ANALYZING MOTION

POSITION

Position describes the location of an object according to a choice of zero point and positive direction. The zero point is called the origin and upwards is commonly used as the positive direction when analyzing vertical motion. For example, with upward positive, a skydiver in a stationary balloon at an altitude of 12,000 **ft** would have a position of 12,000 **ft**, if we called the ground the origin. If we chose 12000 **ft** as the origin then the position of the skydiver would be zero. If we chose 24,000 **ft** as the origin, the skydiver would have a position of -12,000 **ft**. It doesn't matter where you put the origin or which direction is positive as long as you keep them both consistent throughout your analysis.



Initial position, final position, and displacement of a skydiver from jump to landing. Ground level was chosen as the origin and upwards as the positive direction. Image adapted from Balloon over Straubing, Germany by Runologe, "Gabriel Skydiving" By Gabriel Christian Brown, "EOD parachute jump" Petty Officer 3rd Class Daniel Rolstonvia and Parachute precise landing by Masur, all via Wikimedia Commons

Let's say we placed the origin at the ground and chose upwards as positive, as in the diagram above. If we are analyzing the motion of the skydiver starting just as they jump to just as they land, then their initial position (x_i) would 12,000 **ft** and their final position (x_f)would be 0 **ft.** The change in position would be -12,000 **ft** because they moved 12,000 **ft** downward, which is the negative direction. We call the change in position the displacement (Δx) and we calculate the displacement as:

(1) $\mathbf{\Delta x = x_f - x_i}$

For our skydiver example we have:

(2) $\mathbf{\Delta x} = 0\mathbf{ft} - 12,000\mathbf{ft} = -12,000\mathbf{ft}$

VECTORS

As we analyze motion we are beginning to see that it's important to keep track of directions for different quantities of motion like position and displacement, just like we do for forces. Just as with forces, we will make the symbols for these vectors **bold** when writing equations to remind ourselves that these quantities include directions.

DISTANCE AND DISPLACEMENT

It may seem odd that we have introduced displacement as a new word for distance that something travels, but there is actually an important distinction between the two terms. The distance and displacement are sometimes equal, but not always. For example, the distance our skydiver traveled from balloon to ground was 12,000 **ft**, but their displacement was -12,000 **ft.** If we analyze the motion of the skydiver starting from when they got into the balloon on the ground to when they landed after the jump then the distance traveled by the skydiver would be 24,000 **ft**. However, the displacement would be 0 **ft** because their initial and final positions were the same. *The distance traveled can be greater than, or equal to the displacement, but it can never be less.* This distinction arises because direction matters in calculating displacement, but not in measuring distance.

Reinforcement Exercise

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1. Balloon over Straubing, Germany by Runologe, via wikimedia commons
2. "Gabriel Skydiving" By Gabriel Christian Brown [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], from Wikimedia Commons
3. "EOD parachute jump" Petty Officer 3rd Class Daniel Rolston (https://www.dvidshub.net/image/1465626) [Public domain], via Wikimedia Commons
4. Parachute precise landing by Masur [Public domain], via Wikimedia Commons

VELOCITY

INSTANTANEOUS SPEED AND VELOCITY

The maximum speed reached by a body (or any object) falling under the influence of both gravitational force and air resistance is often called terminal velocity or terminal speed. In everyday life we often use speed and velocity to mean the same thing, but they actually have different meanings in physics. Velocity is the rate at which the position is changing and speed is the rate at which distance is covered. Objects cannot travel negative distances so the speed will always be positive. However, position can become more negative, as was the case for our example skydiver, so velocity can be negative. The speed at any instant in time is known as the instantaneous speed. The instantaneous velocity is just the instantaneous speed with a direction included. For example, if at some point our skydiver reached a terminal speed of 89 **MPH**, then their terminal velocity would be 89 **MPH** *downward* or -89 **MPH** for our choice of downward as the negative direction.

INITIAL AND FINAL VELOCITY

Just as we defined initial position and final position for the section of an object's motion that we are analyzing, we can also define initial velocity and final velocity. For example, if we analyze the skydiver's motion from jump until they reach an example terminal speed of 180 **MPH**, then the initial velocity of our skydiver was zero and the final velocity was -180 **MPH**.

AVERAGE VELOCITY

Sometimes we are interested in the average velocity over some amount of time rather than the instantaneous velocity at a single time. To calculate the average velocity for a section of an objects motion we need to divide the change in position (displacement) by the time interval (Δt) over which the it occurred.

(3) $$\mathbf{v_{ave}} = \frac{\mathbf{\Delta x}}{\Delta t} = \frac{\mathbf{x_f} - \mathbf{x_i}}{\Delta t}$$

Velocities will be negative when the displacement is negative, as was the case for our skydiver's trip from balloon to ground. The negative displacement of our skydiver would result in a negative average velocity during their trip from balloon to ground. This makes sense, as we should be expecting a negative velocity for our skydiver because downward was chosen as our negative direction and the skydiver was moving downward.

AVERAGE SPEED AND VELOCITY

Sometimes average speed and average velocity are the same, but sometimes they are not. Speed is the rate at which distance is traveled so to calculate average speed we divide the distance traveled by the time required for the travel. Remembering that we use displacement rather than distance in calculating average velocity, we can see that speed and velocity are different. For example the velocity of the skydiver in our example is negative on the way down because displacement is negative, however we cannot say the diver actually traveled a negative distance, so the average speed is positive.

Everyday Examples

Let's imagine the skydiver in our example rode a hot air balloon upward for 21 minutes, then jumped and fell for 2.0 minutes, then opened their parachute and drifted downward for 5.0 minutes before landing. Let's calculate the average speed and average velocity for the entire trip in feet per minute.

The average speed is the total distance covered divided by the total time, which would be 24,000 **ft** divided by 27 minutes for an average speed of: 860 **ft/min**.

The average velocity would be the total displacement divided by the total time. The skydiver started and ended the trip on the ground, so the total displacement for the round trip was zero, therefore the average velocity for the trip was *zero*! Comparing this average velocity to the average speed of 860 **ft/min** we can really see why its important to distinguish between instantaneous vs. average and speed vs. velocity.

Reinforcement Activities

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CHAPTER 62.

ACCELERATED MOTION

ACCELERATION

After the air resistance becomes large enough to balance out a skydiver's weight, they will have no net force. From Newton's First Law we already know that an object's inertia prevents a change in velocity unless it experience a net force, so from that point when the forces are balanced and onward, the skydiver continues at a constant velocity until they open their parachute.

During the initial part of a skydive, before the drag force is large enough to balance out the weight, there is a net force so their velocity changes. The rate at which the velocity changes is known as the acceleration. Note that students often confuse velocity and acceleration because they are both rates of change, so to be specific: *velocity defines the rate at which the position is changing and acceleration defines the rate at which the velocity is changing.* We can calculate the average acceleration (***a***) during a certain time interval (*Δt*) by subtracting the initial velocity ($\boldsymbol{v_i}$) from the final velocity ($\boldsymbol{v_f}$) to get the change in velocity (***Δv***) and then dividing by the time interval (*Δ*t):

(1) $$\mathbf{a}=\frac{\mathbf{\Delta v}}{\Delta t}=\frac{\mathbf{v_f}-\mathbf{v_i}}{\Delta t}$$

Everyday Example

Let's calculate the average acceleration during the roughly 2 seconds it takes a parachute to fully open and slow a skydiver from 120 **MPH** to 6.0 **MPH**. First let's remember that the skydiver is moving in our negative direction so the initial and final velocities should be negative. Also, lets convert to meters per second: $\mathbf{v_f}=-6.0\,\mathbf{mph}=-2.7\,\mathbf{m/s}$ and $\mathbf{v_i}=\mathbf{v_f}=-120\,\mathbf{mph}-54\,\mathbf{m/s}$.

Starting with our definition of acceleration:

$$\mathbf{a}=\frac{\mathbf{v_f}-\mathbf{v_i}}{\Delta t}$$

Inserting our values:

$$\mathbf{a}=\frac{-2.7\,\mathbf{m/s}-(-54\,\mathbf{m/s})}{2\,\mathbf{s})}$$

The two negatives in front of the 54 **m/s** make a positive, and then we calculate a value.

$$\mathbf{a} = \frac{-2.7\,\mathbf{m/s} + (54\,\mathbf{m/s})}{2\,\mathbf{s})} = 26\,\mathbf{m/s/s}$$

We now get a chance to see that the units of acceleration are **m/s/s** or equivalently **m/s^2**

ACCELERATION DIRECTION

The direction of acceleration depends on the direction of the change in velocity. If the velocity becomes more negative, then acceleration must be negative. This is the case for our skydiver during the first part of the jump; their speed is increasing in the negative direction, so their velocity is becoming more negative and therefore acceleration is negative. Conversely, if an object moves in the negative direction, but slows down, the acceleration is positive, *even though the velocity is still negative*! This was the case for our skydiver just after opening their parachute, when they still moved downward, but were slowing down. Slowing down in the negative direction means the velocity is becoming less negative, so the acceleration must be positive. All of the possible combinations of velocity direction and speed change and the resulting acceleration are summarized in the following chart:

Table Showing Possible Acceleration Directions

Initial direction of motion (initial velocity direction)	Speed change	Direction of Acceleration
positive	speeding up	positive
positive	slowing down	negative
negative	speeding up	negative
negative	slowing down	positive

Reinforcement Exercises

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CHAPTER 63.

ACCELERATING THE BODY

NEWTON'S SECOND LAW OF MOTION

Newton's First Law tells us that we need a net force in order to create an acceleration. As you might expect, a larger net force will cause a larger acceleration, and the same net force will give a smaller mass a greater acceleration. Newton's Second Law summarizes all of that into a single equation relating the net force, mass, and acceleration:

(1) $\mathbf{F_{net}} = m\mathbf{a}$

FINDING ACCELERATION FROM NET FORCE

If we know the net force and want to find the acceleration, we can solve Newton's Second Law for the acceleration:

(2) $\mathbf{a} = \frac{\mathbf{F_{net}}}{m}$

Now we see that larger net forces create larger accelerations and larger masses reduce the size of the acceleration. In fact, an object's mass is a direct measure of an objects resistance to changing its motion, or its inertia.

Reinforcement Exercises

FINDING NET FORCE FROM ACCELERATION

Everyday Example: Parachute Opening

In the previous chapter we found that if opening a parachute slows a skydiver from 54 **m/s** to 2.7 **m/s** in just 2.0 **s** of time then they experienced an average upward acceleration of 26 **m/s/s** . If the mass of our example skydiver is 85 **kg**, what is the average net force on the person?

We start with Newton's Second Law of Motion

$$\mathbf{F_{net}} = m\mathbf{a}$$

Enter in our values:

$$\mathbf{F_{net}} = (85\,\mathbf{kg})(26\,\mathbf{m/s/s}) = 2200\,\mathbf{N}$$

The person experiences an average net force of 2200 **N** upward during chute opening. When the chute begins to open the body position changes to feet first, which significantly reduces air resistance, so air resistance is no longer balancing the body weight. Therefore, the harness needs to support body weight plus provide the additional unbalanced 2200 **N** upward force on the person. The skydiver's body weight is F_g = 85 **kg** x 9.8 **m/s/s** = 833 **N**, so the force on them from the harness must be 2833 **N.** That force is actually more than three times greater than their body weight, but is distributed over the wide straps that make up the leg loops and waist loop of the harness, which helps to prevent injury.

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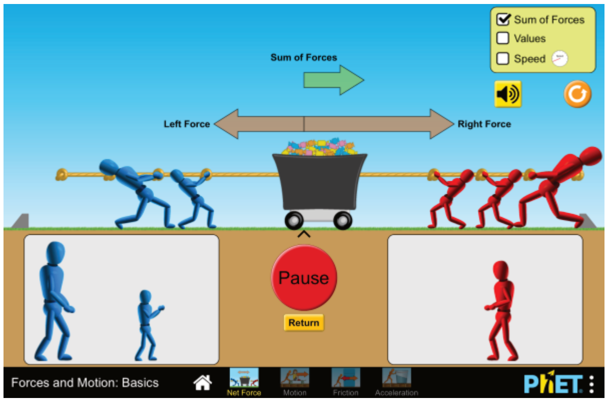
Reinforcement Exercises

Check out this simulation to see how forces combine to create net forces and accelerations:



FREE-FALL ACCELERATION

In the absence of air resistance, heavy objects do not fall faster than lighter ones and all objects will fall with the same acceleration. Need experimental evidence? Check out this video:

It's an interesting quirk of our universe that the same property of an object, specifically its mass, determines both the force of gravity on it and its resistance to accelerations, or inertia. Said another way, the inertial mass and the gravitational mass are equivalent. That is why we the free-fall acceleration for all objects has a magnitude of 9.8 $\mathbf{m/s/s}$, as we will show in the following example.

Everyday Example: Free-Falling

Let's calculate the initial acceleration of our example skydiver the moment they jump. At this moment they have the force of gravity pulling them down, but they have not yet gained any speed, so the air resistance (drag force) is zero. The net force is then just gravity, because it is the only force, so they are in free-fall for this moment. Starting with Newton's Second Law:

(3) $$\mathbf{a} = \frac{\mathbf{F_{net}}}{m}$$

Gravity is the net force in this case because it is the only force, so we just use the formula for calculating force of gravity

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near the surface of Earth, add a negative sign because down is our negative direction ($\mathbf{F_g} = -mg$), and enter that for the net force: :

$$\mathbf{a} = \frac{-mg}{m} \quad (4)$$

We see that the mass cancels out,

$$\mathbf{a} = \frac{-\cancel{m}g}{\cancel{m}} = -g = -9.8\frac{\mathbf{m}}{\mathbf{s^2}} \quad (5)$$

We see that our acceleration is negative, which makes sense because the acceleration is downward. We also see that the size, or magnitude, of the acceleration is *g = 9.8* ***m/s***^{2}**.** We have just shown that *in the absence of air resistance, all objects falling near the surface of Earth will experience an acceleration equal in size to 9.8* ***m/s***^{2}*, regardless of their mass and weight.* Whether the free-fall acceleration is -9.8 **m/s/s** or +9.8 **m/s/s** depends on if you chose downward to be the negative or positive direction.

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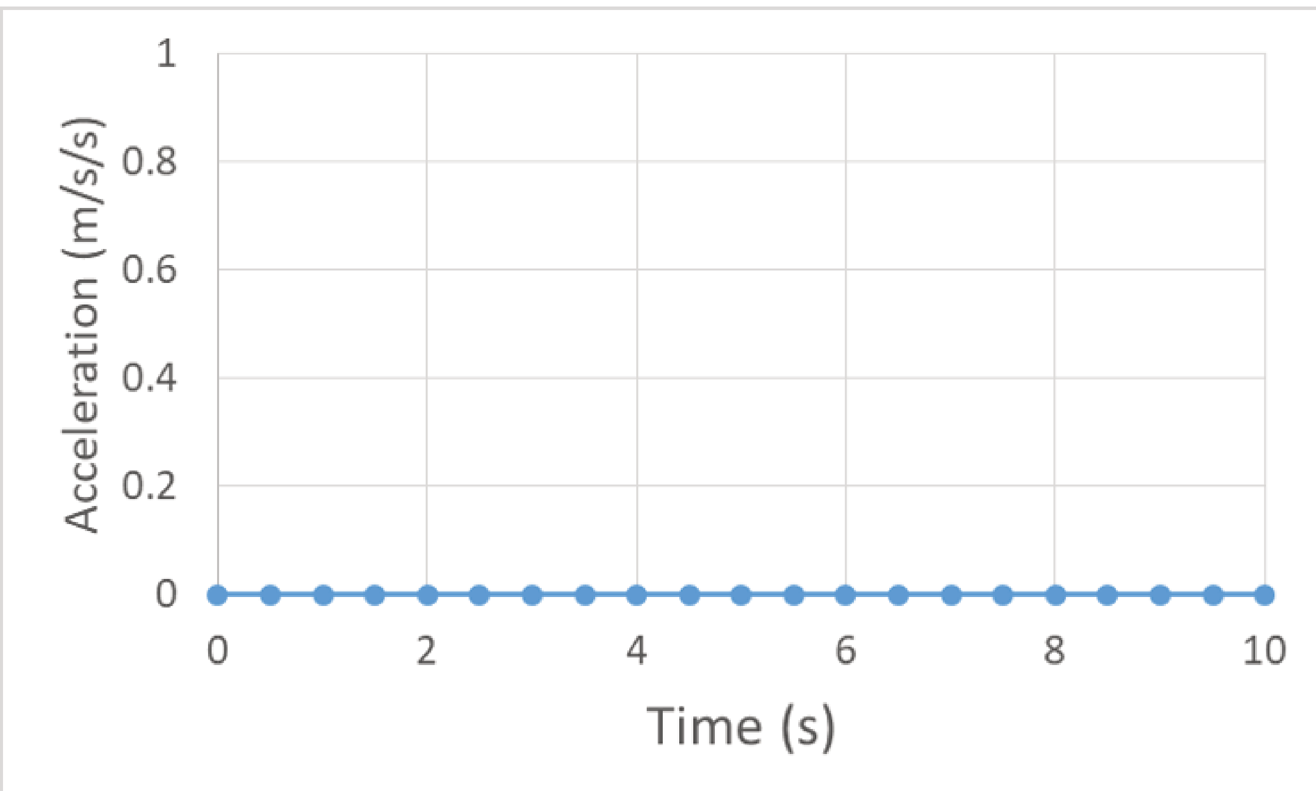
CHAPTER 64.

GRAPHING MOTION

BASIC MOTION GRAPHS

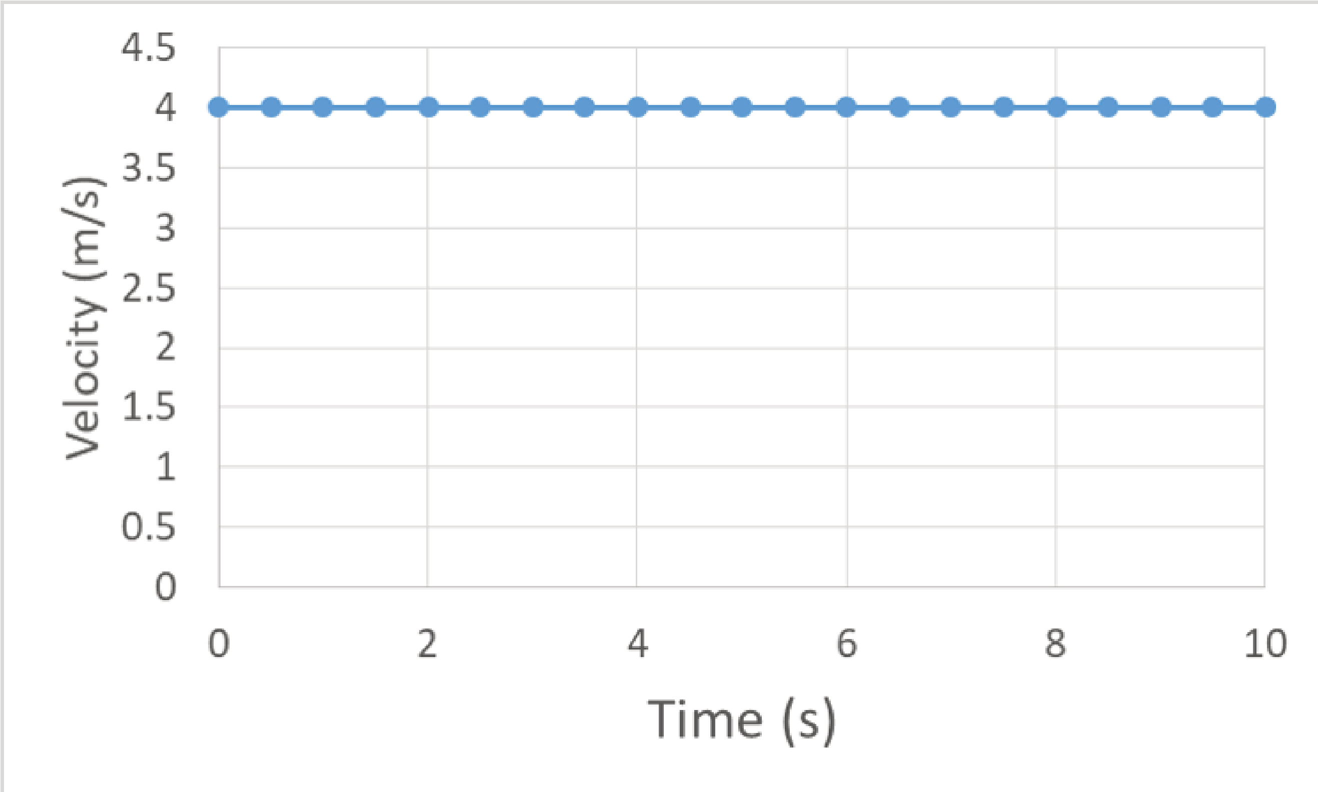
Motion graphs are a useful tool for visualizing and communicating information about an object's motion. Our goal is to create motion graphs for our example skydiver, but first let's make sure we get the basic idea.

We will start by looking at the motion graphs of on object with an initial position of 2 **m** and constant velocity of 4 **m/s**. An object moving at constant velocity has zero acceleration, so the graph of acceleration vs. time just remains at zero:



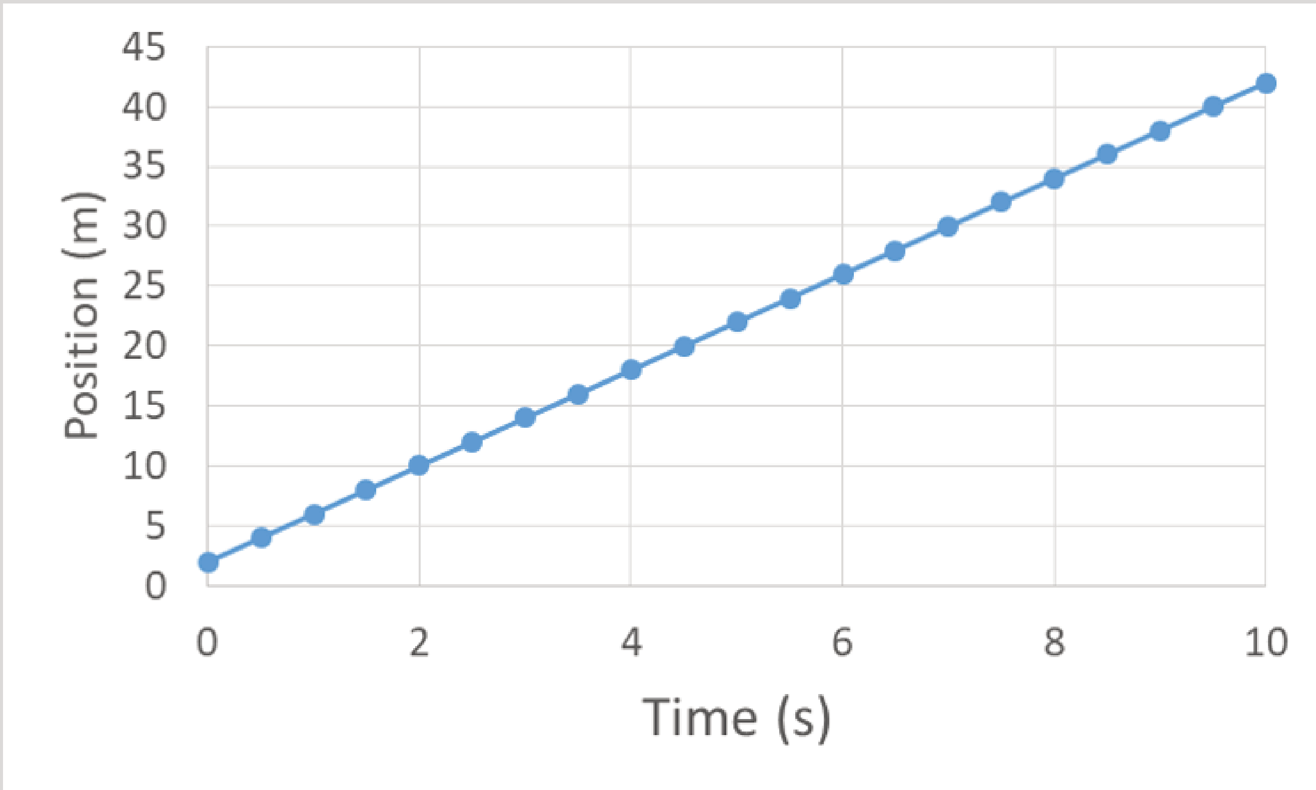
The acceleration vs. time graph for an object with constant velocity is flat at zero.

The velocity is constant, so the graph of velocity vs. time will remain at the 4 **m/s** value:



*The velocity vs. time graph is flat (constant) at 4 **m/s**.*

Velocity is the rate at which position changes, so the position v. time graph should change at a constant rate, starting from the initial position (in our example, 2 **m**). The slope of a motion graph tells us the rate of change of the variable on the vertical axis, so we can understand velocity as the slope of the position vs. time graph.



*The position vs. time graph is linear with a slope that is equal to the 4 **m/s** velocity and intercept that is equal to the 2 **m** initial position. The graph crosses position 10 meters at time 2 seconds.*

Reinforcement Exercises

Now let's look at motion graphs for an object with constant acceleration. Let's give our object the same initial position of 2 **m**, and initial velocity of 4 **m/s**, and now a constant acceleration of 2 **m/s/s**. The acceleration vs. time remains constant at 2 **m/s/s**:

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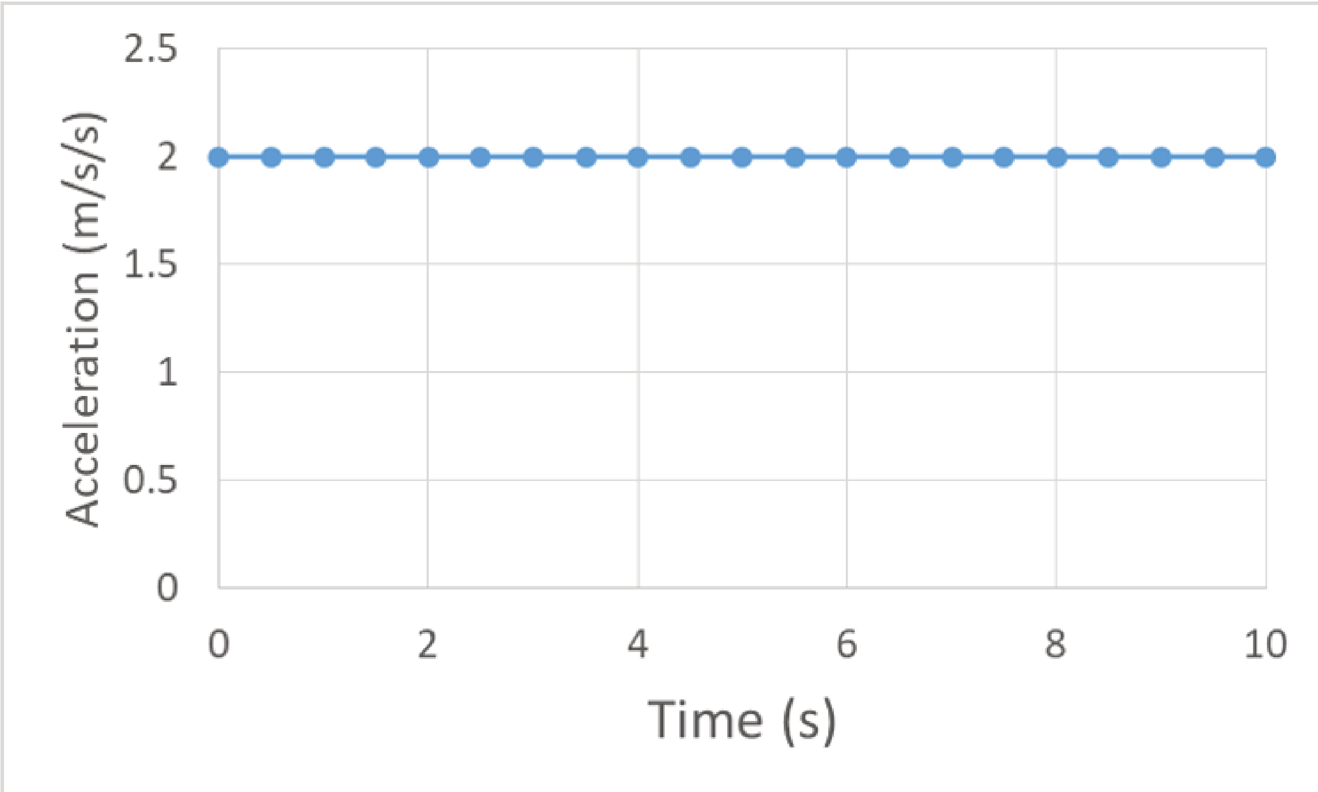
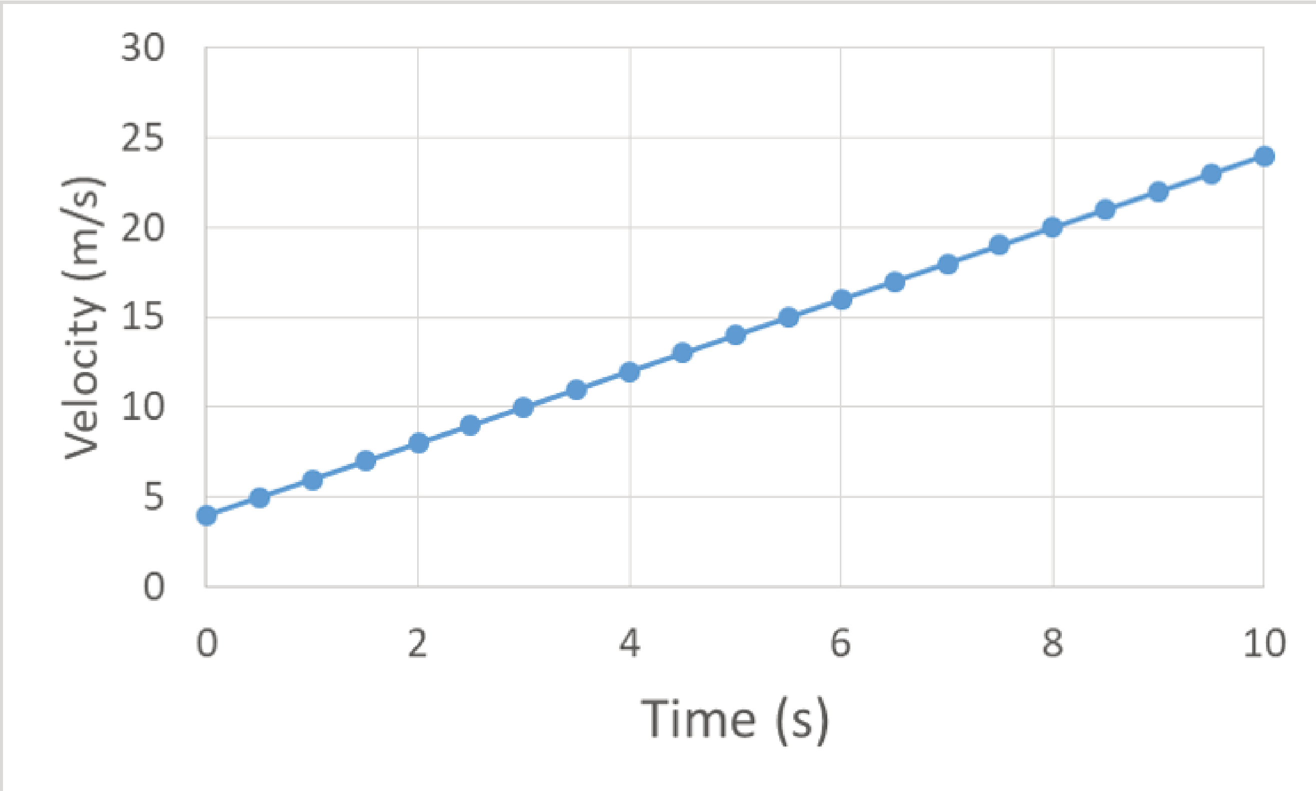


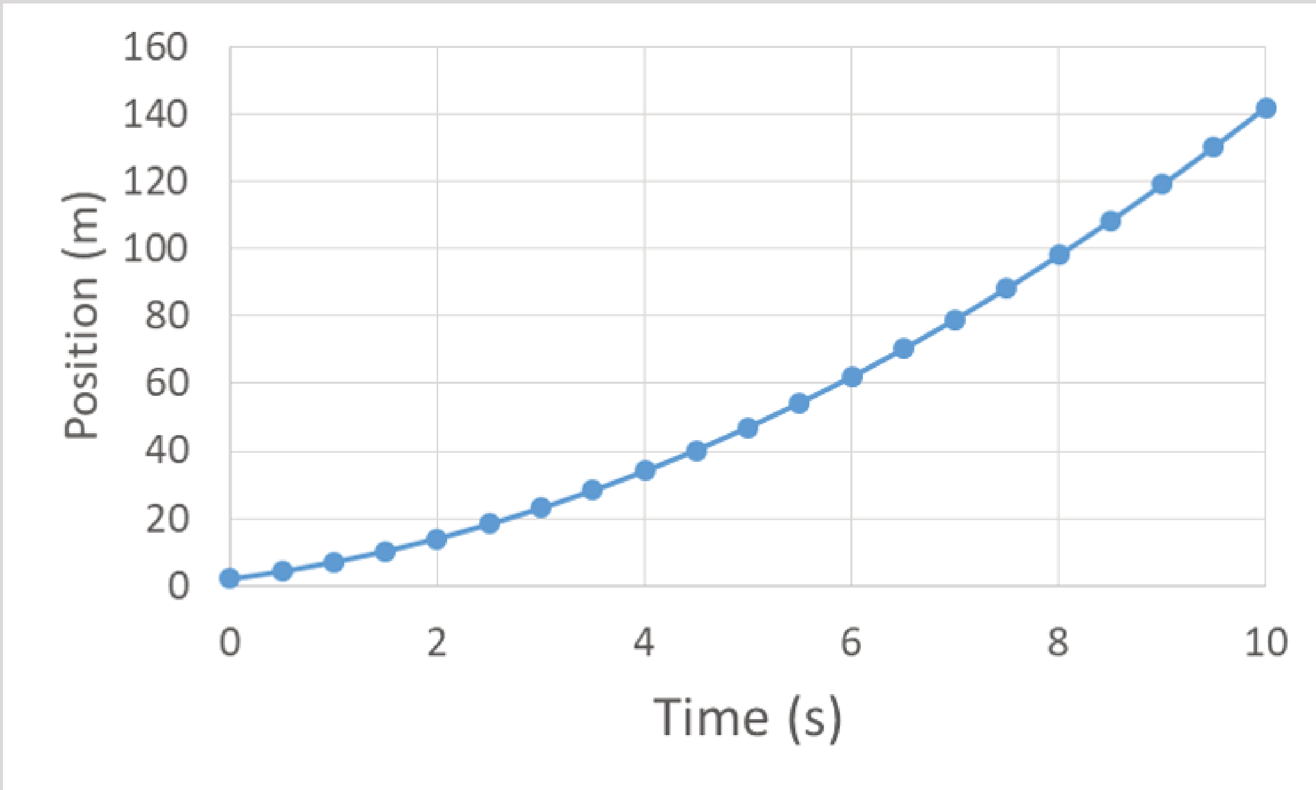
The acceleration vs. time graph is flat at the acceleration value, in this example 2 ***m/s/s***

Acceleration is the rate at which velocity changes, so acceleration is the slope of the velocity vs. time graph. For our constant 2 **m/s/s** acceleration the velocity graph should have a constant slope of 2 **m/s/s**:



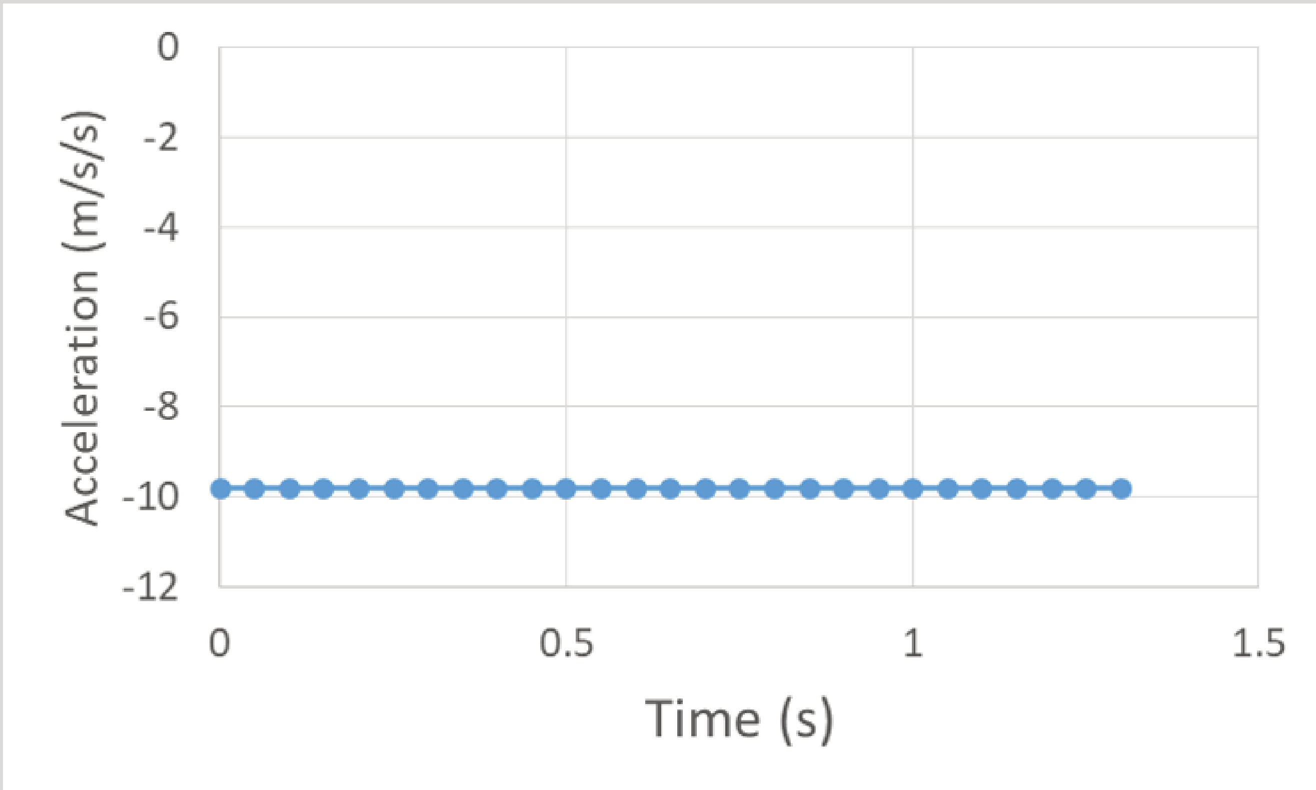
The velocity vs. time graph is linear with a slope equal to the 2 ***m/s/s*** *acceleration value and intercept equal to the initial velocity value of 4* ***m/s****.*

Finally, if the velocity is changing at a constant rate, then the slope of the position graph, which represents the velocity, must also be changing at a constant rate. The result of a changing slope is a curved graph, and specifically a curve with a constantly-changing slope is a *parabolic* curve, or a *parabola*.



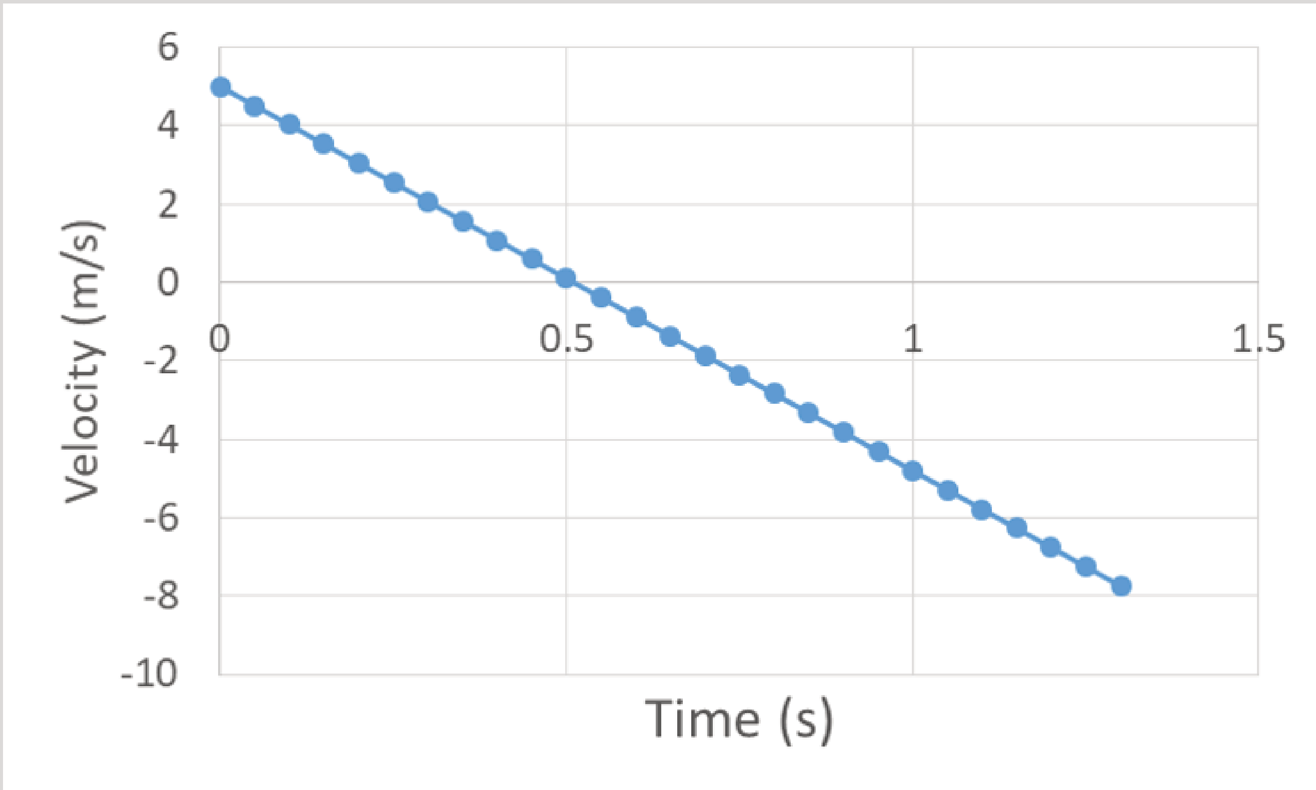
The position vs. time graph of an object with constant acceleration is a parabolic curve. The curvature is upward for positive acceleration and downward for negative accelerations. The intercept is the initial position, in this example 2 ***m****.*

We haven't made motion graphs for the situation of constant position because they are relatively unexciting. The position graph is constant at the initial value of position, the velocity graph is constant at zero and the acceleration graph is also constant at zero. Let's end this section with some interesting graphs – those of an object that changes direction. For example, an object thrown into the air with an initial velocity of 5 **m/s**, from an initial position of 2 **m** that then falls to the ground at 0 **m**. Neglecting air resistance, the acceleration will be constant at negative *g*, or -9.8 **m/s/s**.



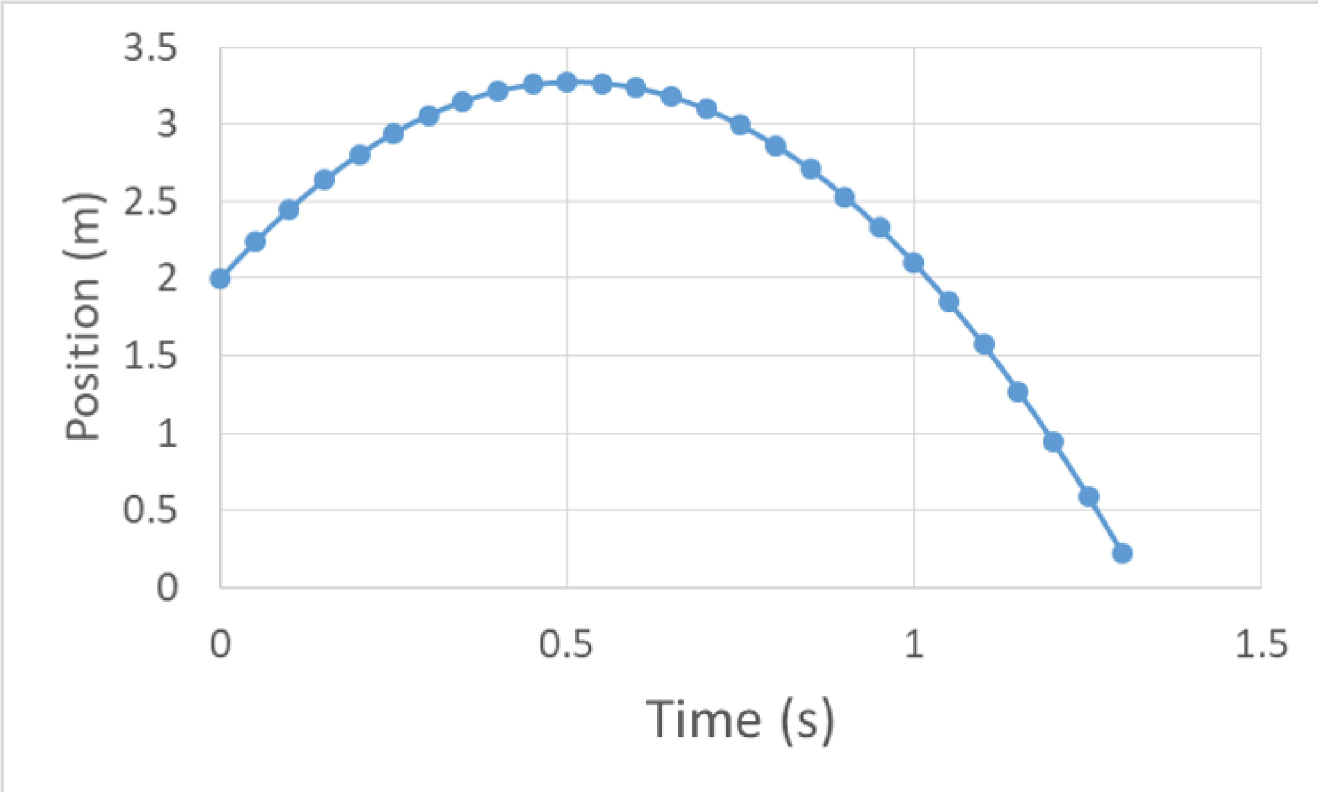
The acceleration vs. time graph for an object is flat at -9.8 m/s/s (for a choice of downward as the negative direction).

The velocity will be positive, but slowing down toward zero, cross through zero as the object turns around, and then begin increasing in the negative direction.



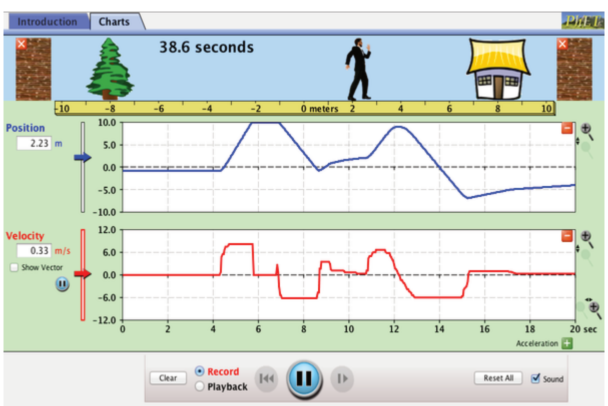
The velocity vs. time graph starts at 5 ***m/s*** *and decreases linearly crossing through zero at roughly 0.5* ***s*** *and then becoming more negative with time in linear fashion and reaching – 5* ***m/s*** *just after 1* ***s****. The slope is -9.8* ***m/s/s****.*

The position will increase as the object moves upward, then decrease as it falls back down, in a parabolic fashion because the slope is changing at a constant rate (acceleration is constant so velocity changes at a constant rate, so the slope of the position graph changes constantly).



The position vs. time graph is a parabola with downward curvature starting at 2 ***m****, peaking near 3.3* ***m*** *at roughly 0.5* ***s****, passing back through 2* ***m*** *just after 1* ***s****, and hitting the ground just after 1.3* ***s****.*

Check out this interactive simulation of a moving person and the associated motion graphs:

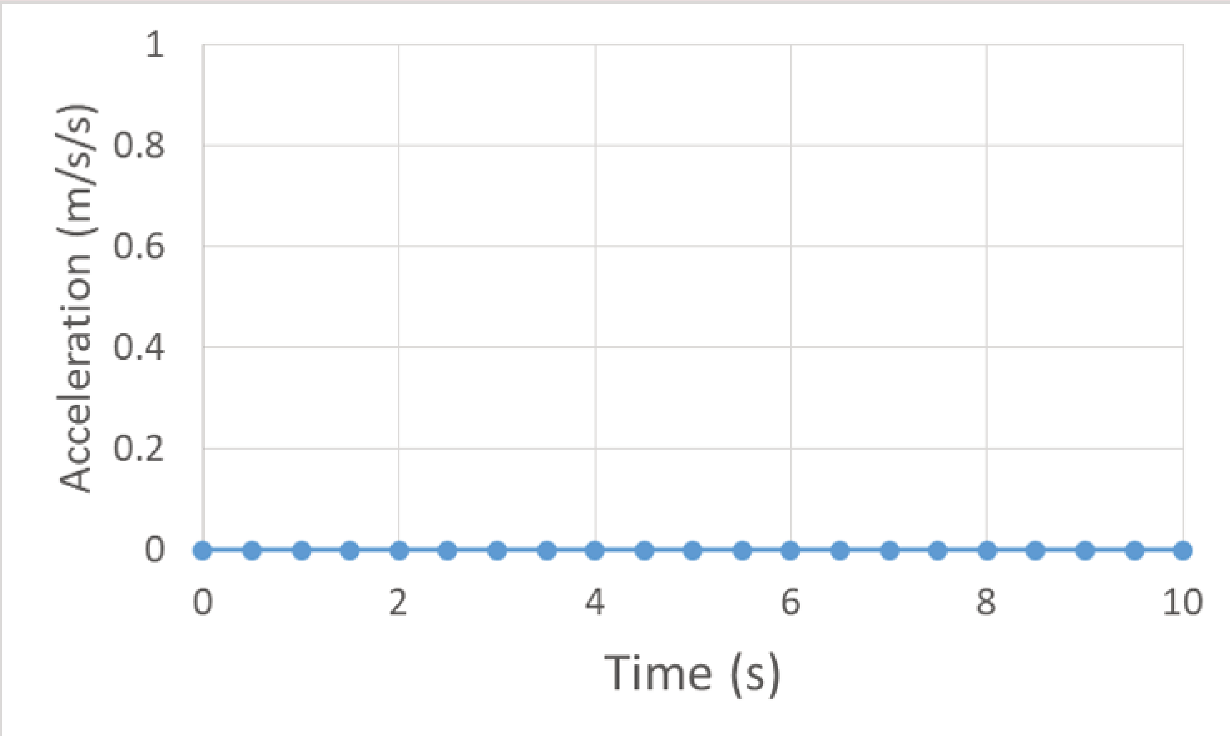


Reinforcement Exercises

Everyday Example: Terminal Velocity

Let's look at the motion graphs for our skydiver while they are at a terminal velocity of -120 **MPH**, which is about 54 **m/s**. Let's set our initial position for this analysis to be the position where they hit terminal velocity.

Acceleration is zero because they are at terminal velocity:



Acceleration vs. time graph is constant (flat) at zero.

Velocity is constant, but negative:

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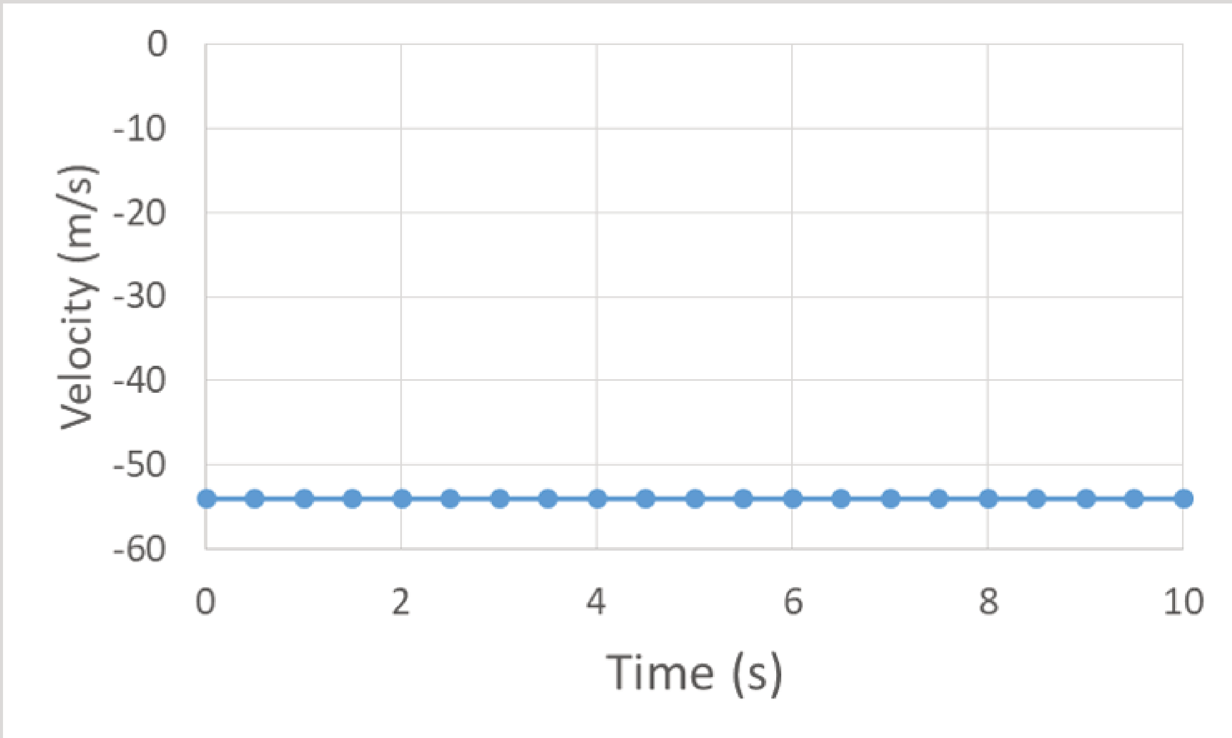
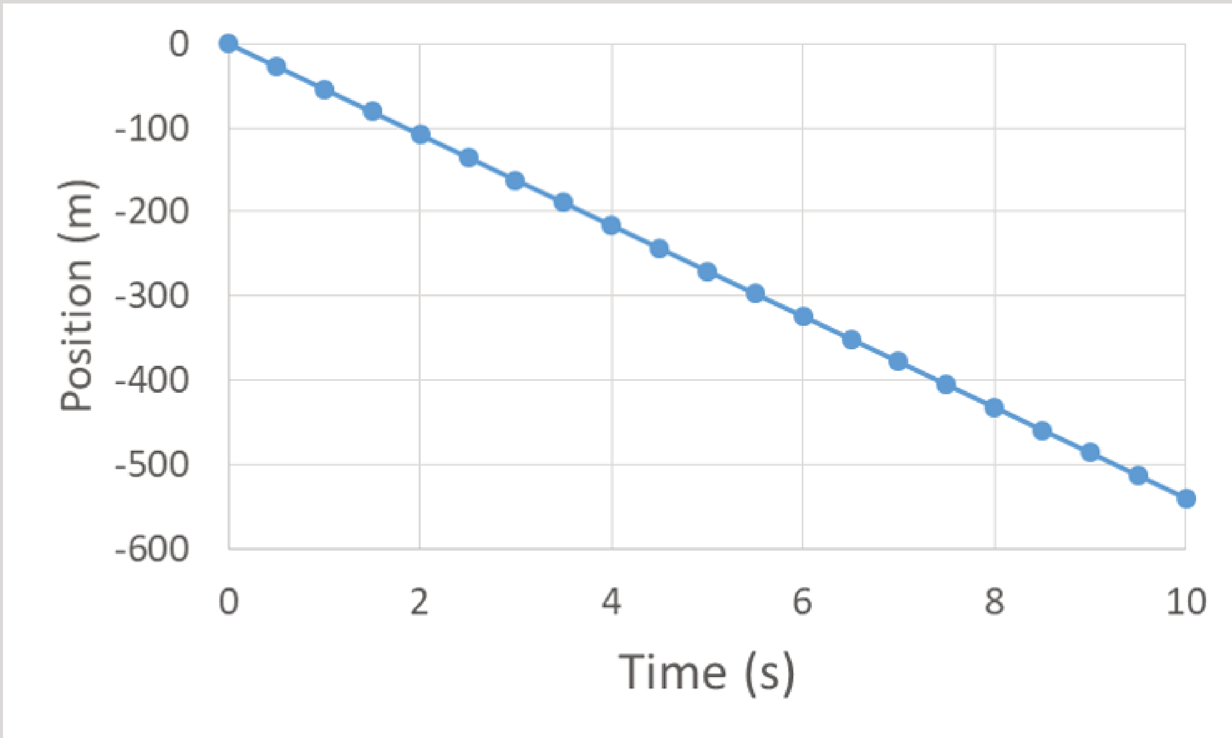


Velocity vs. time graph is constant near -52 ***m/s****.*

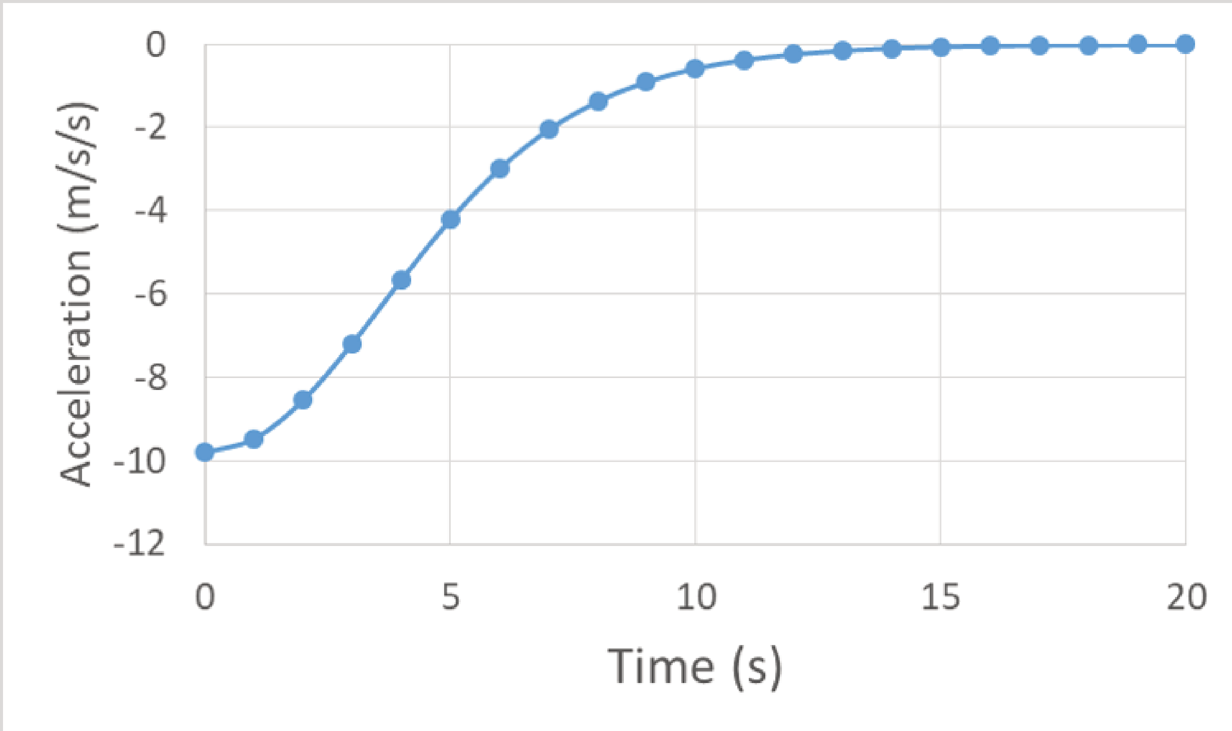
And position changes at a constant rate, becoming more negative with time.



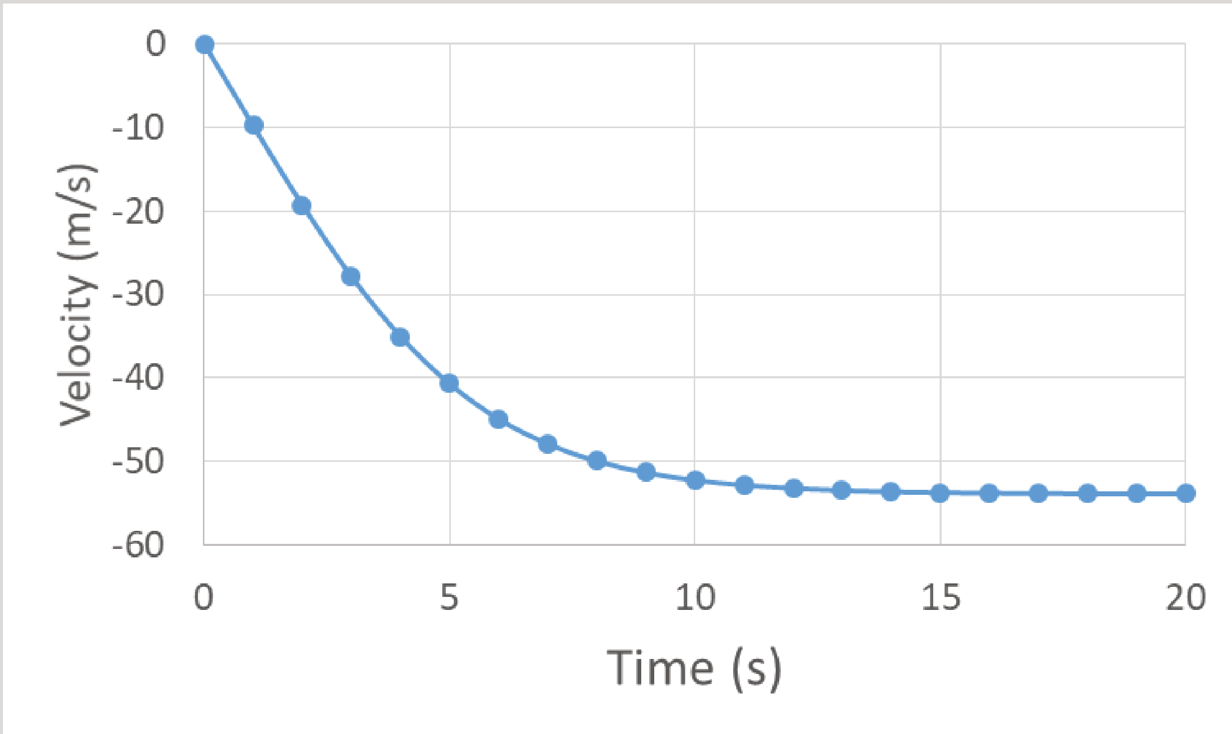
Position vs time graph decreases linearly from zero to -520 ***m*** *after 10* ***s****.*

Everyday Example: Full Skydive

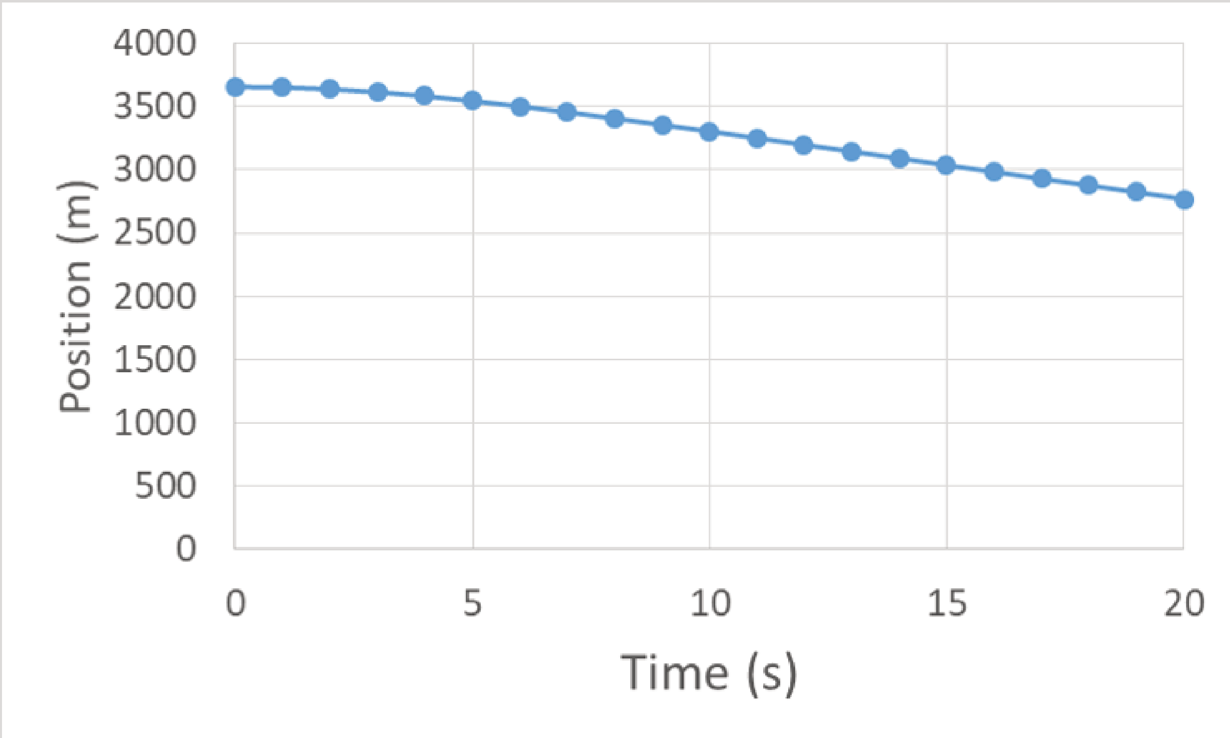
Now let's look at the motion graphs for our skydiver prior to reaching terminal velocity, starting from the initial jump.



The acceleration vs. time curve starts at -9.8 **m/s/s** because in the first instant there is no drag force so the diver is momentarily in free-fall. As speed is gained, the drag force increases, cancelling out more of the weight, so the acceleration trends toward zero and becomes indistinguishable from zero near 15 **s**.



The velocity vs. time curve starts at zero and because the initial speed was zero. Velocity remains negative because the motion is downward, but the slope is not constant like it would in free-fall because the acceleration is not constant like in free-fall. That is because the drag force is growing as the velocity increases, eventually become as large as the weight, so the velocity eventually begins to level off and approach a constant 52 ***m/s****.*



The position vs time curve starts at 3660 ***m*** *and decreases toward zero with a negative and gradually steepening slope (moving down and speeding up). After after 20* ***s*** *the skydiver nears position 2750* ***m*** *and the slope becomes constant at of 52* ***m/s,*** *indicating terminal velocity. Note that we have converted our [pb_glossary id="4047"]initial position[/pb_glossary] of 12,000* ***ft*** *to the equivalent 3660* ***m.***

CHAPTER 65.

QUANTITATIVE MOTION ANALYSIS

KINEMATICS

We now know to find average acceleration of an object by finding the net force and applying Newton's Second Law. Once the acceleration is known, we can figure out how the velocity and position change over time. That process is known as kinematics and the equations we use to relate acceleration, velocity, position, and time are known as the kinematic equations. Let's take a look at a few of them one-by-one.

Based on our definition of acceleration as the rate of change of the velocity we can calculate the change in velocity during a time interval as the acceleration multiplied by the length of the time interval:

(1) $\mathbf{\Delta v} = \mathbf{a}\Delta t$

Reinforcement Exercises

If a person has an acceleration of 5.0 **m/s/s**, how much does their velocity change in 2.0 **s**?

We can find the current velocity by adding the expression for change in velocity to the initial velocity:

(2) $\mathbf{v_f} = \mathbf{v_i} + \mathbf{a}\Delta t$

Reinforcement Exercises

If the person in the previous exercise has an initial velocity of 2.0 **m/s**, what is their new velocity after the 2.0 **s**?

We can calculate the average velocity during the interval as the average of the initial and final velocities:

(3) $\mathbf{v_{ave}} = \dfrac{\mathbf{v_i} + \mathbf{v_f}}{2}$

Reinforcement Exercises

What is the average velocity of the person in the previous exercise?

Using the definition of velocity as the rate of change of position we can calculate the change in position during a time interval as the average velocity during the interval multiplied by the length of the time interval.

(4) $\mathbf{\Delta x} = \mathbf{v_{ave}}\Delta t$

Reinforcement Exercises

What is the change in position of the person in the previous exercises?

Adding the above expression for change in position to the initial position allows us to calculate the final position after any time:

(5) $\mathbf{x_f} = \mathbf{x_i} + \mathbf{v_{ave}}\Delta t$

Reinforcement Exercises

If the person in the previous exercises started at a position of 4 **m/s**, what is their final position?

We can combine everything the from previous steps into a single equation that can save some time on some problems. It looks like this:

(6) $$\mathbf{x_f} = \mathbf{x_i} + \mathbf{v_i}\Delta t + \frac{1}{2}\mathbf{a}(\Delta t)^2$$

To get the above equation we used equation (3) to replace the average velocity with the expression for average velocity:

(7) $$\mathbf{x_f} = \mathbf{x_i} + \frac{\mathbf{v_i} + \mathbf{v_f}}{2}\Delta t$$

Using equation (2) we can then replace the final velocity:

(8) $$\mathbf{x_f} = \mathbf{x_i} + \frac{(\mathbf{v_i} + \mathbf{v_i} + \mathbf{a}\Delta t)}{2}\Delta t$$

After some simplification we are there:

(9) $$\mathbf{x_f} = \mathbf{x_i} + \mathbf{v_i}\Delta t + \frac{1}{2}\mathbf{a}(\Delta t)^2$$

Reinforcement Exercises

Everyday Example

After leaving a friend's 3rd story apartment you get to your car and realize that you have left your keys in the apartment. You call your friend and ask them to drop the keys out the window to you. We want to figure out how long it will take the keys to reach you and how fast they will be falling when they get there. The third story window is about 35 **ft** off the ground. We can convert to meters and use our previously stated acceleration for falling objects, *g* =9.8 **m/s/s**, or we can stick with feet and use *g* = 32 **ft/s/s**, so let's do that.

Starting from our last equation from the work we did above:

$$\mathbf{x_f} = \mathbf{x_i} + \mathbf{v_i}\Delta t + \frac{1}{2}\mathbf{a}(\Delta t)^2$$

We choose upward as our positive direction and the ground as our origin, therefore our initial position is 35 **ft** and our final position is 0 **ft**. The keys are dropped from rest, so our initial velocity is zero. Putting the zeros into the equation above we have:

$$0 = \mathbf{x_i} + 0 + \frac{1}{2}\mathbf{a}(\Delta t)^2$$

Now we can isolate the time variable:

(10) $$t^2 = \frac{-2\mathbf{x_i}}{\mathbf{a}}$$

Take the square root to find the time

(11) $$t = \sqrt{\frac{-2\mathbf{x_i}}{\mathbf{a}}}$$

Entering our known values we can find the fall time. We will use -32 **ft/s/s** for our acceleration because the acceleration due to gravity is downward and we have chosen upward as the positive direction.

(12) $$t = \sqrt{\frac{-2(35\,\mathbf{ft})}{-32\,\mathbf{ft/s/s}}} = 1.479\,\mathbf{s} = 1.5\,\mathbf{s}$$

Lastly, we can find the velocity of the keys using equation (2) above

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$$\mathbf{v_f} = \mathbf{v_i} + \mathbf{a}\Delta t = 0 + (32\,\mathbf{ft/s/s})(1.479\,\mathbf{s}) = 47\,\mathbf{ft/s} \tag{13}$$

The final velocity of 47 **ft/s** is about 32 **MPH**. If the keys smack your hand at that speed, it will hurt. There are techniques you could use to prevent injury in such a situation, and those techniques will be the topic of the next Unit.

In solving the previous example we found an equation to calculate the time required for an object with a certain acceleration to reach a final position of zero when starting from a known initial position. Among other things, this allows us to calculate the time required to fall to the ground from a certain starting height. That equation will come up often, so lets write it out here:

$$t = \sqrt{\frac{-2\mathbf{x_i}}{\mathbf{a}}} \tag{14}$$

If acceleration is set to -9.8 $\mathbf{m/s/s}$ (or -g), then this equation calculates the free-fall time for a choice of negative as the downward direction.

Reinforcement Exercises

THE JERK

We have learned in the last few chapters that our example skydiver has an initial acceleration of 9.8 $\mathbf{m/s/s}$ and an acceleration of zero after reaching terminal velocity, so between those points the acceleration must be changing. The rate of change of the acceleration is known as the *jerk,* but we won't deal with jerk in this textbook and will instead focus on motion with constant acceleration. However, if we really want to analyze our skydiver's full motion, we will need to somehow deal with a changing acceleration. That's what the next chapter is all about.

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https://openoregon.pressbooks.pub/bodyphysics/?p=1918

CHAPTER 66.

FALLING INJURIES

We started out this chapter by claiming that we would eventually be able to analyze the forces on the body during an impact with a hard surface after a fall. We have reached that point. Let's do it.

Everyday Examples: Forces during a Fall

An 80**kg** person falls 0.80 **m** from a hospital bed onto a concrete floor. First-off, how much time do they have to reach out and grab something?

In the previous chapter we found an equation for calculating the fall time when starting from rest:

(1) $$t = \sqrt{\frac{-2\mathbf{x_i}}{\mathbf{a}}}$$

Entering our values:

(2) $$t = \sqrt{\frac{-2(0.80\,\mathbf{m})}{-9.8\,\mathbf{m/s/s}}} = 0.404\,\mathbf{s}$$

If you do the lab at the end of this Unit you will find that 0.4 **s** is near the limit of human reaction time. If reaction time was impaired for any reason, which is common in hospital patients, it's likely that the person would hit the ground without grabbing something to slow down.

How fast will the person be moving when they hit the floor (what is the impact speed)? Using another kinematic equation:

(3) $\mathbf{v_f} = \mathbf{v_i} + \mathbf{a}\Delta t$

And entering our values:

(4) $\mathbf{v_f} = 0 + (-9.8\,\mathbf{m/s/s})(0.404\,\mathbf{s}) = -3.96\,\mathbf{m/s}$

The velocity comes out negative as expected because they are moving downward. The hard floor will bring them to a stop in just a fraction of a second, even if they are able to get their arms out to hit first. A reasonable estimate would be about 0.2 **s** (more on this in the next unit). What is the person's average acceleration during impact?

Using the same equation as before:

(5) $\mathbf{v_f} = \mathbf{v_i} + \mathbf{a}\Delta t$

But now solving for acceleration:

(6) $$\mathbf{a} = \frac{\mathbf{v_f} - \mathbf{v_i}}{\Delta t}$$

And entering our values:

(7) $$\mathbf{a} = \frac{0 - (-3.96\mathbf{m/s})}{0.2\,\mathbf{s}} = 19.8\,\mathbf{m/s/s}$$

Now we are ready to calculate the average net force on the person. We'll start from Newton's Second Law:

(8) $$\mathbf{F_{net}} = m\mathbf{a}$$

Entering our values:

(9) $$\mathbf{F_{net}} = (80\,\mathbf{kg})(19.8\,\mathbf{m/s/s}) = 1584\,\mathbf{N}$$

Finally, what force does the floor apply (as a normal force) to the person's back to achieve that net force, despite their weight?

We recognize that the the net force is the result of the upward normal force plus the downward weight.

(10) $$\mathbf{F_{net}} = \mathbf{F_N} + \mathbf{F_g}$$

We solve for the normal force:

(11) $$\mathbf{F_N} = \mathbf{F_{net}} - \mathbf{F_g}$$

Now we need to calculate the weight, keeping in mind that is negative because it is downward:

(12) $$\mathbf{F_g} = -mg = -(80\,\mathbf{kg})(9.8\,\mathbf{m/s/s}) = -784\,\mathbf{N}$$

Finally entering values for net force and weight to get the normal force:

(13) $$\mathbf{F_N} = 1584\,\mathbf{N} - (-784\,\mathbf{N}) = 2368\,\mathbf{N}$$

That is more than three times the body weight. We will see in the next chapter that the peak force is actually much greater than the average force during impacts like this, so in fact this situation is actually worse than our calculations indicate. Now we see why patient falls must be avoided.

CHAPTER 67.

NUMERICAL SIMULATION OF SKYDIVING MOTION*

Our goal for this chapter is to understand how we created the previously shown graphs of acceleration, velocity, and position of our example skydiver, even though the net force and acceleration changes throughout. We will use a numerical simulation that ties together just about everything we have learned so far in this unit to achieve this goal. We already know that the initial velocity is zero and therefore the initial drag force is zero. With no drag force in the first moment of the jump, the diver is in free fall and the acceleration is just *g* in the downward direction, or -9.8 **m/s/s** . We can then calculate the velocity after a short time interval Δt as:

$$\mathbf{v_1} = 0 + g\Delta t$$

We have made theassumption that the acceleration during this interval was constant, even though it wasn't, but if we choose a time interval that is very small compared to the time over which the acceleration changes significantly, then our result is a good approximation. A time interval of one second will satisfy this condition in our case, so we now calculate the velocity at the end of the first one second interval:

$$\mathbf{v_1} = 0 + g(1\,\mathbf{s})$$

Now that we have a velocity we can calculate the air resistance at the start of the second interval using our previously stated values for human drag coefficient, cross-sectional area, and the standard value for air density:

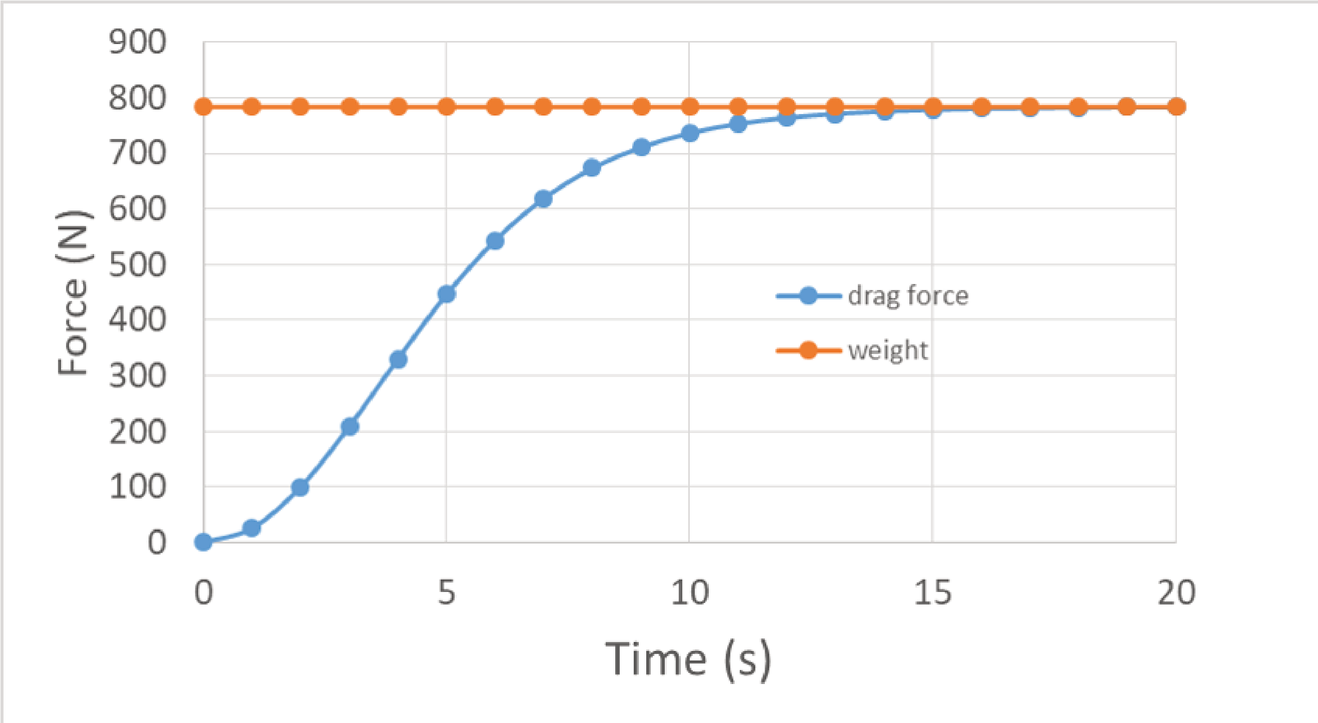
$$\mathbf{F_{d,2}} = \frac{1}{2}C_d\rho A_x v_1^2 = \frac{1}{2}(1)(1.2\,\mathbf{kg/m^3})(0.45\mathbf{m^2})(.98\,\mathbf{m/s})^2 = 0.259\,\mathbf{N}$$

Now that we have a drag force due to air resistance we can use Newton's Second Law to calculate the acceleration at the start of the second interval. We have only two forces, drag and gravity and we will use our previously stated skydiver mass of 80 **kg**:

$$\mathbf{a_2} = \frac{\mathbf{F_{net}}}{m} = \frac{\mathbf{F_{d,2}} + \mathbf{F_g}}{m} = \frac{\mathbf{F_{d,2}} - mg}{m} = \frac{25.9\,\mathbf{N} - (80\,\mathbf{kg})(9.8\,\mathbf{m/s/s})}{80\,\mathbf{kg}} = 9.48\,\mathbf{m/s/s}$$

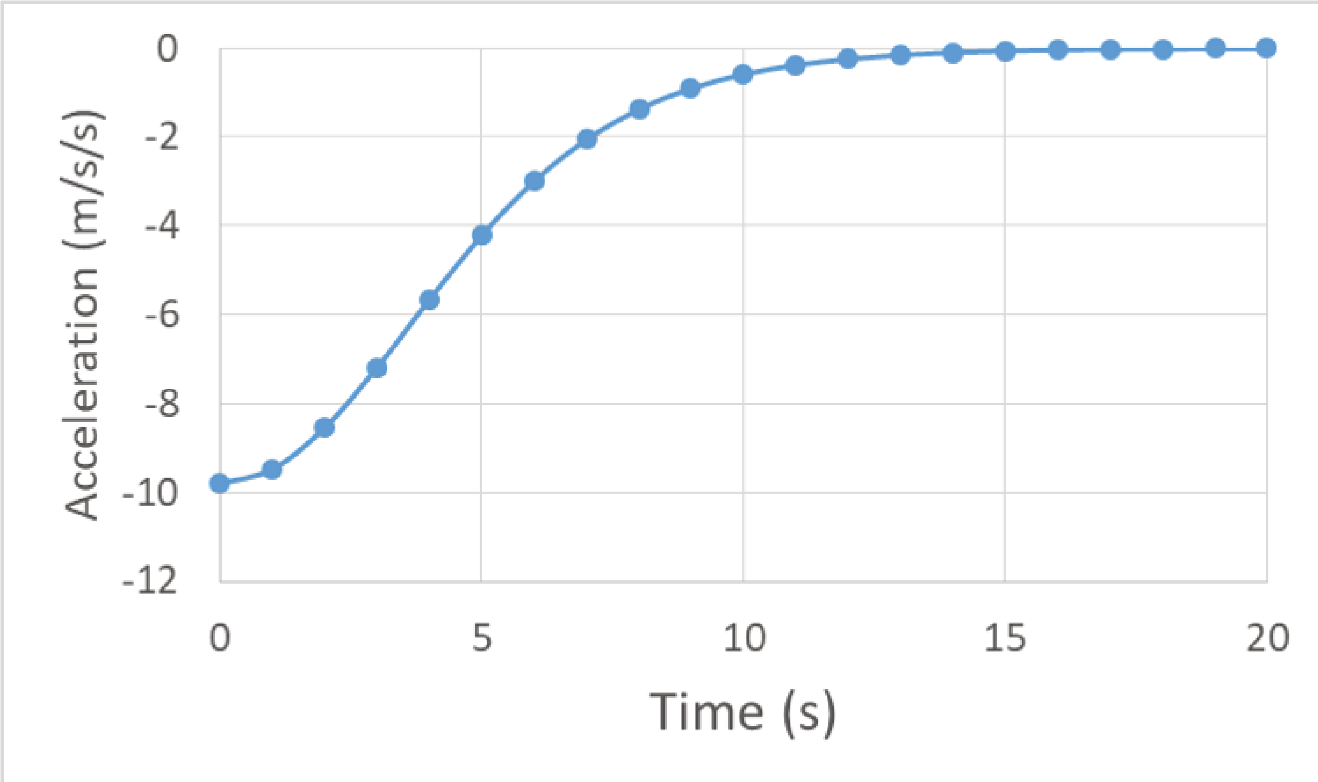
Now we just continue this iterative process of using acceleration and velocity values from the previous interval to calculate new velocity, drag force, and acceleration for next interval.

Using the data produced by the simulation we can graph the drag force. Showing the weight on the same graph we can see how the drag force approaches the weight.



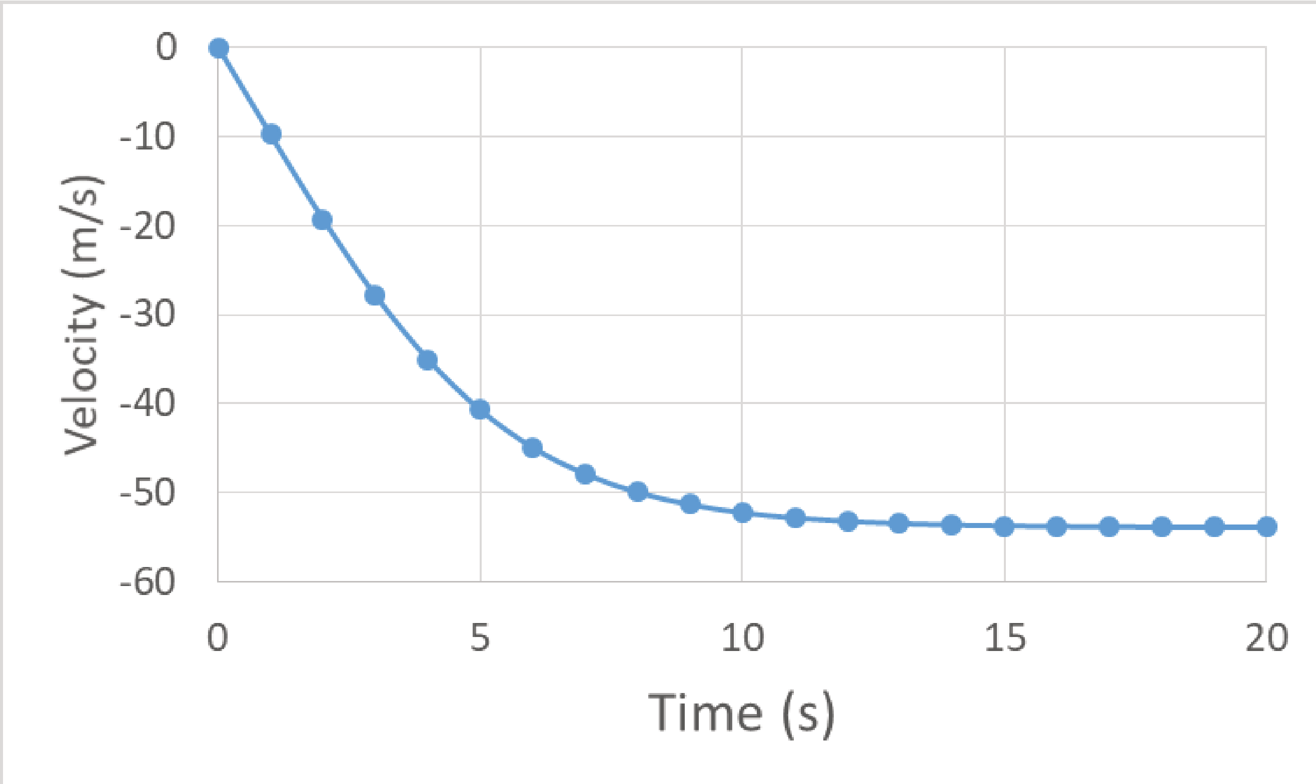
An example force vs. time curve for both drag and weight during a skydive. Weight is constant at 800 **N***. Drag starts at zero, increases with increasing slope (upward curvature), reaches an inflection point near 4* **s***, and continues to increase, but now with decreasing slope, and becomes indistinguishable from the weight value near 15* **s***.*

We can also use the data to create motion graphs for the skydive and see that the acceleration gradually transitions from -9.8 **m/s/s** to zero as drag force increases.



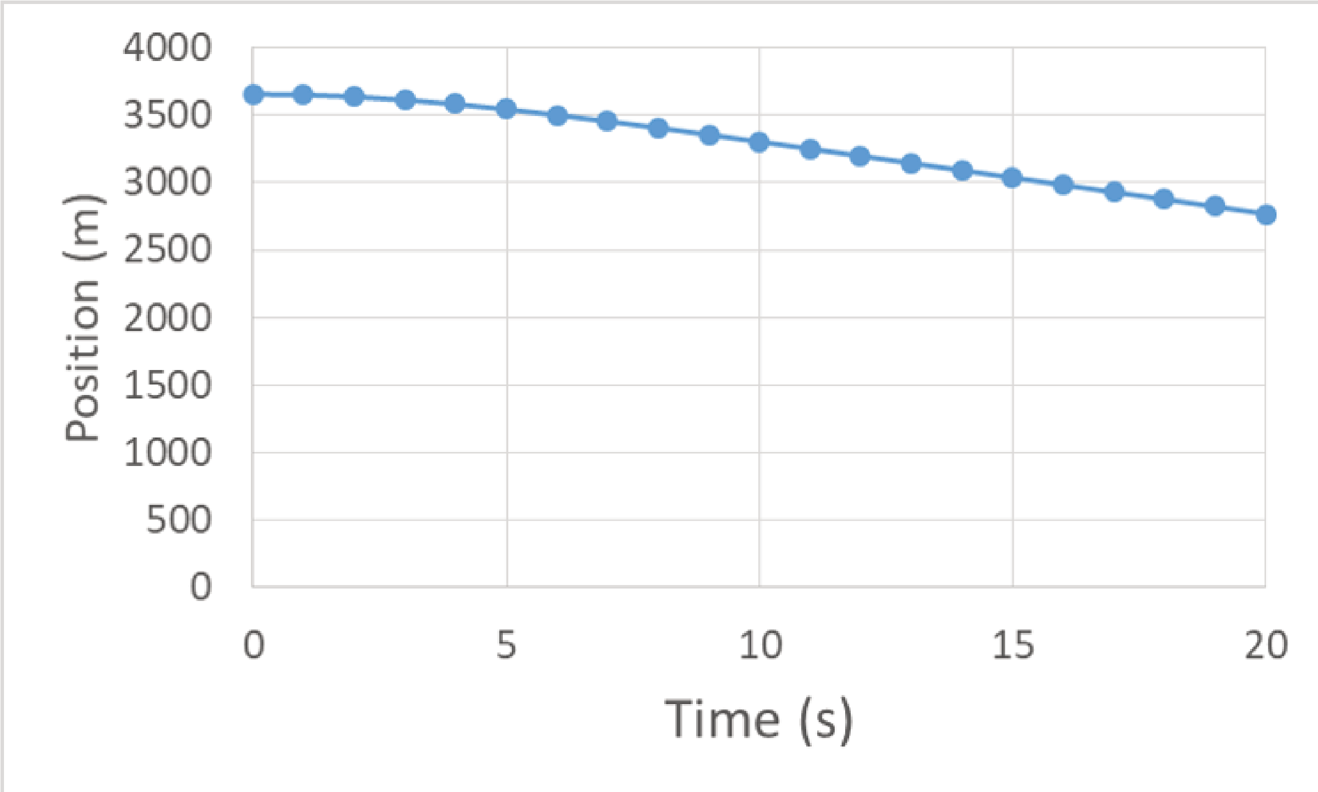
The acceleration vs. time curve replicates the shape of the force curve, but starts at -9.8 ***m/s/s****, increases toward zero with increasing slope (upward curvature), reaches an inflection point near 4* ***s****, and continues to increase, but now with decreasing slope, and becomes indistinguishable from zero near 15* ***s****.*

We see that velocity is always negative and the speed is always increasing, but the slope becomes less steep because the acceleration is decreasing with time:



The velocity vs. time curve starts at zero and increases roughly linearly in the negative direction until near 4 ***s*** *when it begins to level off and approach a constant 52* ***m/s****.*

Finally we can see that the position graph eventually becomes linear as terminal velocity is reached. (Note that we have converted our initial position of 12,000 **ft** to the equivalent 3660 **m**)



The position vs time curve starts at 3660 **m** *and decreases toward zero with a negative and gradually steepening slope, nearing position 2750* **m** *and slope of 52* **m/s** *after 20* **s***.*

CHAPTER 68.

UNIT 7 REVIEW

Key Terms and Concepts

Drag force

Drag coefficient

Air resistance

Dynamic equilibrium

Newton's First Law (Law of Inertia)

Inertia

Terminal Speed

Position

Displacement

Speed

Velocity

Acceleration

Newton's Second Law

Numerical Simulation

Learner Outcomes

1. Define position, velocity, and acceleration and explain how they are related.
2. Define free-fall acceleration and calculate the drag force on objects moving through fluids.
3. Translate motion graphs into descriptions of motion in terms of position, velocity and acceleration. Translate descriptions of motion into motion graphs.
4. Apply kinematics and Newton's Second Law of Motion to analyze and predict 1-D motion.

CHAPTER 69.

UNIT 7 PRACTICE AND ASSESSMENT

Outcome 1

1) Explain the difference between distance and displacement.

2) Explain how velocity relates to position and how acceleration relates to velocity.

Outcome 2

3) An object is thrown into the air and then caught. Assume the speed is slow enough that air resistance is negligible.

a) How much speed does the object lose each second on the way up?

b) What is the speed at the peak height?

c) How much speed does the object gain each second as it falls back down?

d) Are the starting and finishing speeds the same?

e) Are the starting and finishing velocities the same?

4) Calculate the drag force on a swimmer moving through water at 0.75 **m/s**. The drag coefficient for a human in the prone position is roughly 0.25. Look up the density of water in standard units and cite your source. Estimate the cross-sectional area of a human for this situation by using your own body or average human body measurements (cite your source).

5) The swimmer above is moving at a constant speed. What is the size and direction of the average force applied to the swimmer by the water due to their swimming motion?

Outcome 3

6) A toddler runs away from a parent at 0.3 **m/s** for 3 **s**, stops for 2 **s** to see if they are being chased.

a) Draw a velocity vs. time graph for the toddler's motion

b) Draw an acceleration vs. time graph for the toddler's motion

c) Draw a position vs. time graph for the toddler's motion (you will need to calculate the displacements that occur during each interval in order to draw this graph).

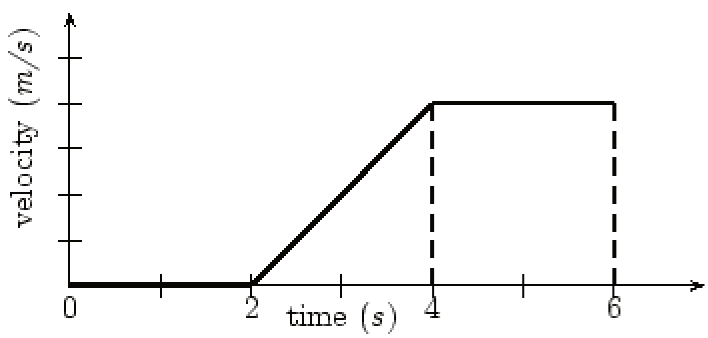
7) Upon realizing they might be chased after the 2 **s** stop, the toddler from the previous exercise begins slowly walking away and increasing speed into a run, reaching a speed of 0.4 **m/s** only 3 **s** later.

a) Complete the acceleration vs. time graph for the toddler's motion, now including this new motion. You may draw a new graph or add to your previous graph in a different color. (You will need to calculate the acceleration during this last part of the toddler's motion in order to complete this graph).

b) Complete the velocity vs. time graph for the toddler's motion. You may draw a new graph or add to your previous graph in a different color. (You will need to use the acceleration you found above to calculate a change in velocity to complete this graph).

c) Complete the position vs. time graph for the toddler's motion. You may draw a new graph or add to your previous graph in a different color. (You will need to use the acceleration you found above to calculate displacements to complete this graph).

8) Describe the motion depicted by the following velocity vs. time graph. The vertical axis tick marks indicate 1 **m/s** intervals, starting from zero **m/s** at the horizontal axis.



*Velocity vs. time graph. The vertical axis marks indicate 1 **m/s** intervals. Image Credit: Uploaded by Riaan at English Wikibooks.*

[1]

9) Draw the acceleration vs. time graph associated with the velocity vs time graph above.

10) Draw the position vs. time graph associated with the previous velocity and acceleration vs. time graphs.

Outcome 4

11) A person with mass of 65 **kg** is out walking two dogs when suddenly the dogs pull in opposite directions. Dog 1 pulls with a force of 500 **N** to the right. Dog 2 pulls with 300 **N** to the left. In order to stay upright, the person has to run to keep their feet underneath their center of gravity (rather than just keep them planted). Therefore, we will ignore friction.

a) Draw a free body diagram of the dog walker. Don't forget to include directions with forces, accelerations, and velocities when answering the following questions.

b) What is the net force on the dog walker?

1. Velocity Graph Uploaded by Riaan at English Wikibooks and transferred from en.wikibooks to Commons., GFDL, is licensed under CC BY-NC-SA 4.0

c) What is the acceleration of the dog walker?
d) What is the velocity of the dog walker after **3 s**?
e) What is the average velocity of the dog walker during this **3 s** period.
f) What distance will the dog walker have moved in 3 **s**?

PART VIII.

UNIT 8: LOCOMOTION

Learning Objectives

1. Describe how locomotion occurs in terms of Newton's Laws of Motion.[2]
2. Apply Newton's Second and Third Laws of motion to analyze the motion of objects.[3]
3. Apply the Law of Conservation of Momentum to analyze the motion of objects.[3]
4. Evaluate and explain strategies for reducing the forces experienced by objects undergoing collisions.[2]

CHAPTER 70.

OVERCOMING INERTIA

Typically an RN like Jolene will walk several miles over the course of a 12 hour shift on the MED floor. Her average speed (v_{ave}) can be calculated as the distance covered divided by the time she worked. If she walks three miles, then her average speed would be:

$$v_{ave} = \frac{distance}{time\,interval} = \frac{3\,miles}{12\,hours} = 0.25\,\mathbf{mph} \quad (1)$$

Jolene's average speed is very different from her instantaneous speed at any one moment in time, which could be anything from zero to about 4.5 **mph** (she tries to avoid running in the hospital). Jolene's instantaneous speed and direction of motion change often as she starts, stops and turns corners. The process of generating, maintaining, and changing motion is known as locomotion.

NEWTON'S THIRD LAW OF MOTION

Newton's First Law tells us that Jolene must experience a net force in order to initiate a change in motion, also known as a change in velocity. We know that Newton's Second Law tells us how to calculate the net force Jolene needs in order to achieve a particular amount of velocity change each second (id="4053″]acceleration[/pb_glossary]). However, Jolene can't apply a net force to herself, so how exactly does Jolene control how much net force she experiences? Newton's Third Law provides the answer. The forces that Jolene experiences must be supplied by the objects around her. The size of the force that Jolene receives from another object, such as the floor or wall, is determined by how hard she pushes against that object. In fact, anytime one object puts a force on a second object, the first object will receive an equal force back, but in the opposite direction. This result is known as Newton's Third Law of Motion. The capacity for using the laws of motion to generate, maintain, and change motion is known as locomotion.

Examples

The astronaut in the video above starts out in static equilibrium relative to the space station. Then she pushed against the wall. The resistance of the wall to being deformed caused it to apply a reactionary normal force back on her. That unbalanced normal force destroyed her state of static equilibrium, overcame her inertia, and caused her velocity to change relative to the station. This example is a unique form of locomotion, but all locomotion depends on this same process of pushing on an object in order receive a push back form the object (even if that object is air or hot exhaust gas from a rocket engine).

Reinforcement Activity

THIRD LAW PAIR FORCES

The equal and opposite forces referenced in Newton's Third Law are known as third law pair forces (or third law pairs).

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Other Third Law pair forces include:

- The Earth pulls down on you due to gravity and you pull back up on the Earth due to gravity.
- A falling body pushing air out of its way and air resistance pushing back on the body.
- You pull on a rope and the rope pulls back against your hand via tension.
- You push on the wall, and the wall pushes back with a normal force.
- A rocket engine pushes hot gasses out the back, and the gasses push back on the rocket in the forward direction.
- You push your hand along the wall surface, and the wall pushes back on your hand due to kinetic friction.
- You push your foot against the ground as you walk, and the floor pushes back against your food due to friction (static if your foot doesn't slip, kinetic if it does).

You may have noticed that in each of the cases above there were two objects listed. This is because *Newton's Third Law pairs must act on different objects.* Therefore, Third Law pair forces cannot be drawn on the same free body diagram and *can never cancel each other out.* (Imagine if they did act on the same object, then they would *always* balance each other out and no object could *ever* have a net force, so no object could ever accelerate!)

Reinforcement Exercises

Draw the free body diagrams necessary to show each force in the Third Law pairs listed above. How many free body diagrams will you need to draw for each Third Law pair? [Hint: keep in mind the rule about free body diagrams and Third Law pairs.]

Reinforcement Exercises

Everyday Example: Headrest

The headrest in your car is not actually designed as a place to rest your head. Its real purpose is to prevent injury. If someone rear-ends your car it will accelerate forward. As a result your body is accelerated forward by normal force and friction from the seat. If the head rest were not there, your head would momentarily remain in place due to inertia as your body moved forward. The lag in head position gives the impression that the head snapped back, but really the body moved forward and left the head behind. Your head does remain attached to your accelerating body though, so the tissues in your neck must provide the large force required to accelerate the head along with the body. According to Newton's Third Law, the tissues of the neck will feel an equal and opposite force to that large force they apply to the head. That large force may damage the tissue (cause a stress larger than the yield stress of the tissue).

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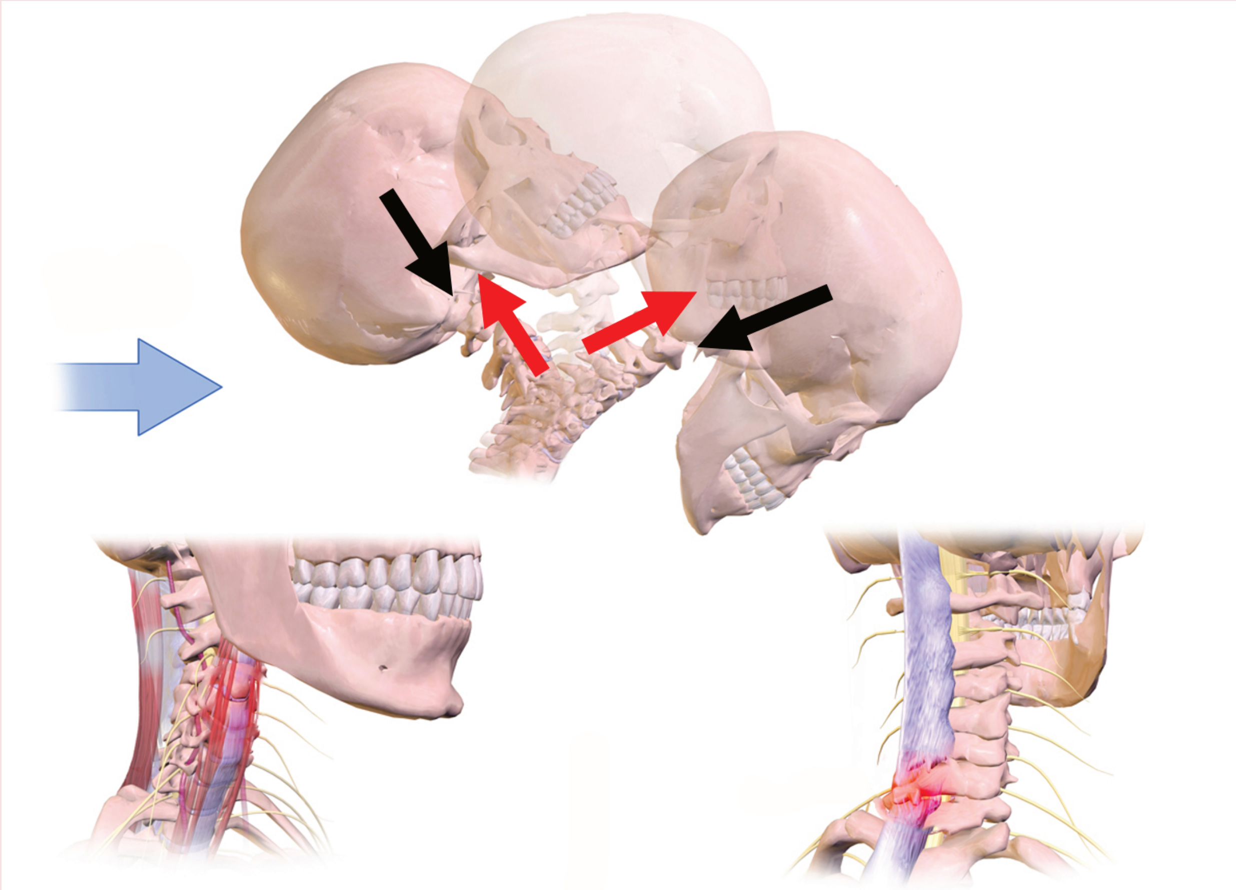

Top: Forces on the head from the neck (black) and on the neck from the head (red) during rapid forward-back motion of the head relative to the body. Bottom: Sites of whiplash injury. Image Credit: 3rd Law Whiplash is a derivative of Whiplash Injury by BruceBlaus, via Wikimedia Commons

[1]

The headrest provides a normal force on your head so that it accelerates along with the body, keeping your head above your shoulders and your neck in a safe position. You can see the importance of the headrest in these crash-test videos:

The headrest doesn't necessarily reduce the acceleration felt by the head as much as provide the force needed to accelerate the head along with the body, so that the neck doesn't have to, thus reducing the third law pair forces between the head and neck.

FALLING AS LOCOMOTION

Notice that the list of third-law pair forces includes the force of gravity on the Earth from you and the force of gravity on you from the Earth (weight), so in fact falling is a form of locomotion. That means that throughout the previous unit on falling we were already studying locomotion, although falling is sort of an uncontrolled, or passive form of locomotion. The next few chapters will help us examine active forms of locomotion like walking, jumping and driving.

1. 3rd Law Whiplash is a derivative of Whiplash Injury by BruceBlaus [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], via Wikimedia Commons

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CHAPTER 71.

LOCOMOTION

ACTIVE LOCOMOTION

Locomotion is based on a combination of Newton's Laws. A body will move with a constant velocity until it experiences a net force (Newton's First Law). A change in body motion is achieved by initiating muscle contraction in order to apply a force against another object, such as the floor or the wall. The other object then applies an equal and opposite reaction force against the body (Newton's Third Law). That reaction force acting on the body adds together with all of the other forces on the body to determine the net force. The net force causes an acceleration that depends on the the body mass according to Newton's Second Law.

Everyday Examples: Responding to a Code Without Slipping

Jolene is walking with a speed of a 2.5 **mph** down the hospital corridor when a code is called over the intercom. She stops then turns around and starts walking the other direction, toward the room where the code was called, at a speed of 4.0 **mph**. If Jolene's mass is 61 **kg** and she tried to make that move very quickly, in only 0.75 **s**, for example, what net force would be applied to her?

We have only been given speeds in the problem, but in order to analyze velocity we need to define direction of motion. Let's assign Jolene's initial direction as the negative direction so her initial velocity was -2.5 **mph**. In that case her final velocity was +4.2 **mph**. We can calculate her change in velocity as:

(1) $\mathbf{\Delta v} = \mathbf{v_f} - \mathbf{v_i} = 4.0\,\mathbf{mph} - (-2.5\,\mathbf{mph} = 6.5 < strong > mph < /strong >$ mph \end{equation*}" title="Rendered by QuickLaTeX.com">

If we convert our answer to units of **m/s** we get: 6.5 **mph** = 2.9 **m/s**. (You can check this yourself using unit analysis or an online unit converter).

Next we calculate Jolene's acceleration using the definition of average acceleration:

$$\mathbf{a} = \frac{\mathbf{\Delta v}}{\Delta t}$$

Entering our values:

$$\mathbf{a} = \frac{2.9\,\mathbf{m/s}}{0.75\,\mathbf{s}} = 3.9\,\mathbf{m/s/s}$$

We find that Jolene's acceleration is 3.9 **m/s/s**, which means that her velocity becomes 3.9 **m/s** more positive each second.

Notice that she was originally moving in the negative direction, so having a velocity that is becoming more positive means that she must have slowed down.

Now we can use Newton's Second Law to calculate the average net force required to provide this acceleration:

$$\mathbf{F_{ave}} = m\mathbf{a}$$

We are now ready to enter our values:

$$\mathbf{F_{ave}} = (61\,\mathbf{kg})(3.9\,\mathbf{m/s}) = 240\,\mathbf{N}$$

Friction is the only horizontal force contributing to the horizontal acceleration Jolene experiences, so the net force would just be equal to the friction force. We can figure out if Jolene would slip by comparing the required net force to the maximum possible static friction force.

First we start with the equation for max static friction force:

$$F_{f,s} = \mu_s F_N$$

Then we divide by the normal force to solve for the friction coefficient:

$$\mu_s = \frac{F_{f,s}}{F_N}$$

Assuming the floor is level and only Jolene's horizontal motion is changing, then the normal force must be balancing Jolene's weight (if these were not balanced then she would have a vertical acceleration as well). For this special case we substitute her weight for the normal force:

$$\mu_s = \frac{F_{f,s}}{mg}$$

Finally we enter our values:

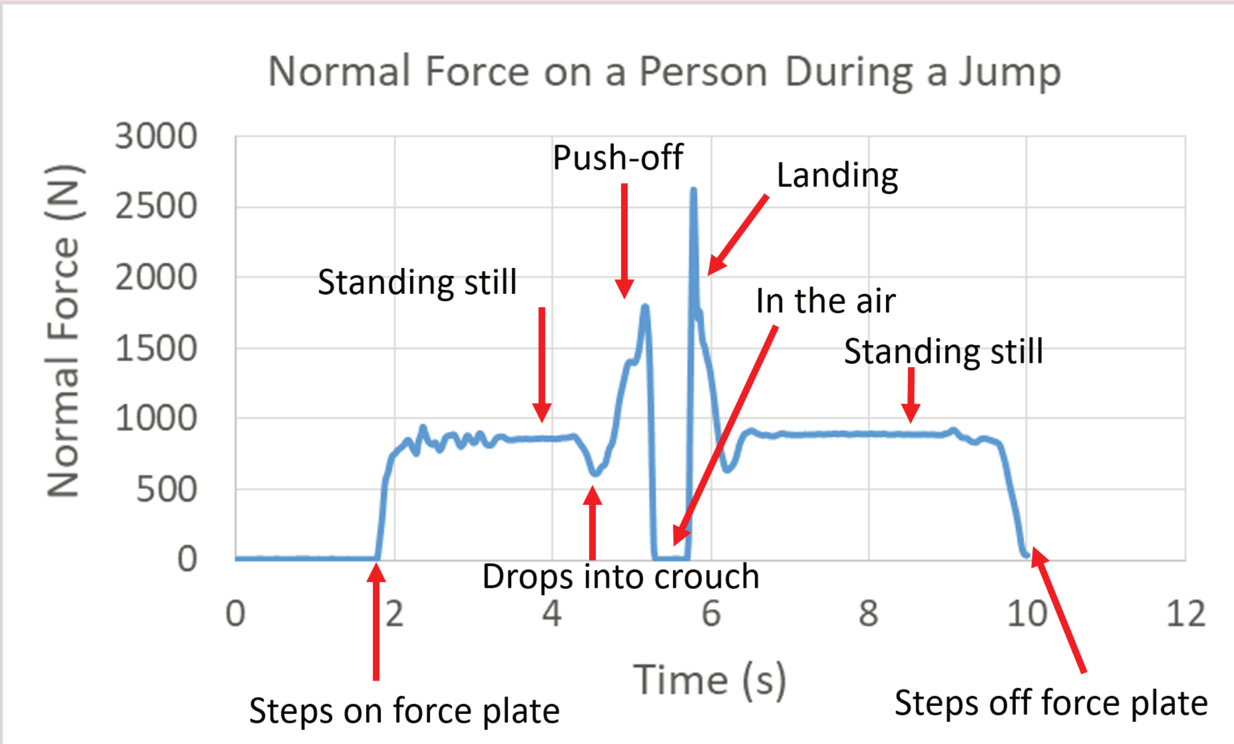
$$\mu_s = \frac{240\,\mathbf{N}}{(61\,\mathbf{kg})(9.8\,\mathbf{m/s/s})} = 0.4$$

Looking up friction coefficients we find that the rubber-concrete friction coefficient is typically 0.6 or greater, so Jolene could likely make this move without slipping.

JUMPING

Everyday Example: Jumping

When a person stands still on flat ground, they are in static equilibrium and the normal force pushing up from the ground is equal to their weight. In order to jump, the muscles of the leg contract to push down against the floor. This downward push results in an equal reactive normal force from the floor, so that now the normal force is greater than body weight a there is an upward net force. Now with an upward net force, the body will experience an upward acceleration. The following graph of the normal force on person was created by jumping and landing on a force plate, which is essentially a extra-tough digital scale that records the normal force that it provides over time.



Normal force from the ground on a person during a jump as recorded by a digital force plate during the experiment described in the following text.

First the jumper steps on the force plate and it reads their weight of about 800 **N**. Then the plate reading dips a couple hundred Newtons because the upward normal force is reduced as they drop down into a crouch, which makes sense because they must accelerate downward to drop down. Next the force peaks to near 1700 **N** they push off hard to stop their downward motion and initiate upward motion. Throughout this stage the normal force is greater than the weight in order to create this upward acceleration. The normal force drops to zero as the body leaves contact with the ground. While in the air gravity provides the net downward force so the acceleration is downward, and the body's upward velocity slows. (After leaving the ground the acceleration is $-g = -9.8$ **m/s/s**). The body eventually turns around as the upward velocity reaches zero, and then begins to move back toward the ground. Landing requires an upward acceleration to stop the downward velocity, so a large upward normal force of over 2500 **N** is produced. The jumper is attempting a "soft landing" and so continues into a crouching position during landing, which causes another couple hundred Newton dip in the normal force at the end of landing. Finally, the normal force equals weight again after landing is complete. Upcoming chapters will talk more about "soft landings" and other methods of injury prevention.

DRIVING

Everyday Example: Driving

In order for your car to accelerate along a flat road, it must have a net horizontal force. What force acts on your car to provide this net force? Remember the force must be on the car from another object, the car can't put a net force on itself (so the answer can't be the engine or any part of the car). Gravity and normal force are external forces on a car, but those forces act vertically and cannot contribute to a horizontal acceleration. The force that acts on your car in the horizontal direction is friction. When the tires attempt to rotate, they push against the ground via friction, and the ground pushes back with an equal reactionary friction force, according to Newton's Third Law. Then, according to Newton's Second Law, that friction force acting on the car causes it to accelerate. The purpose of the throttle, engine, and drive train is to cause the tires to push back on the road in order to receive the forward push from the road in return.

Locomotion in cars is created by the reactionary friction force on the car tires from the road in response to the friction force from the tires on the road. Forward acceleration occurs when the force on the tires from the road is larger than the drag force, providing a net force in the forward direction. Image adapted from Fifth generation Chevrolet Malibu on Interstate 85 in Durham, North Carolina by Ildar Sagdejev (Specious) via wikimedia commons

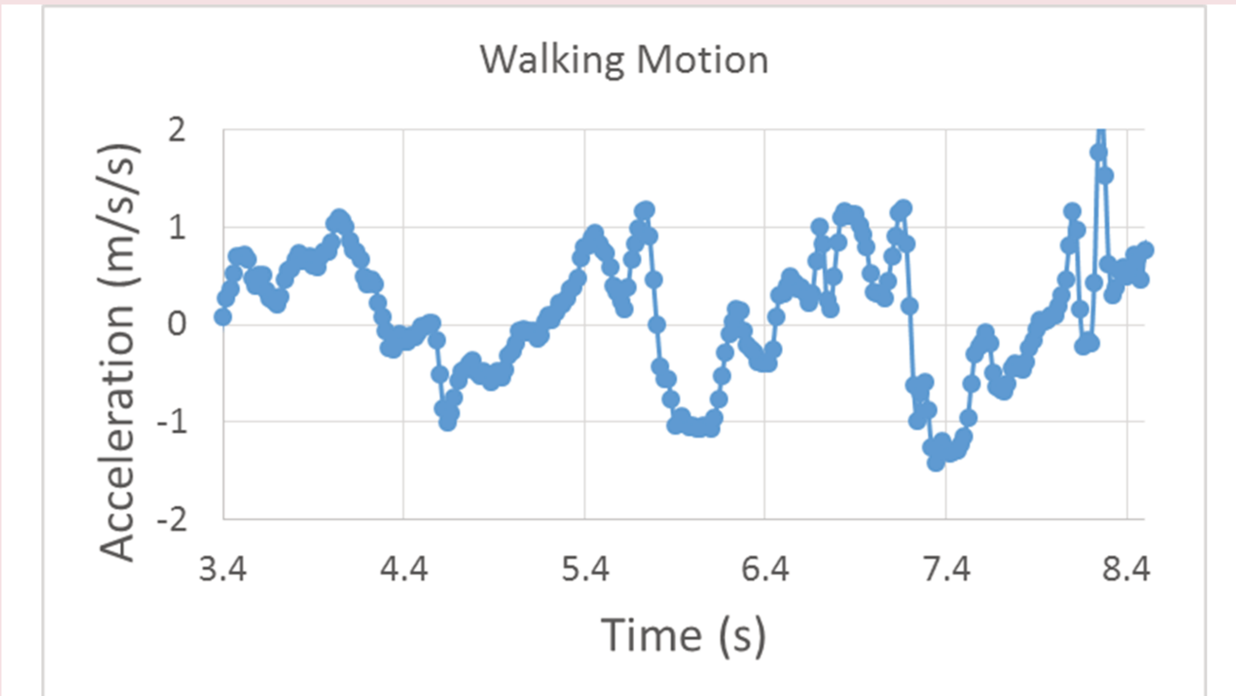
[1]

Also, your car pushes on the air to move it out the way, so according to Newton's 3rd Law, the air puts a drag force back on your car. When the drag force and the friction force on the car are equal the car reaches a constant velocity, sort of like terminal velocity. If you want the car to go faster, you need to increase the friction force on the car from the road, which you achieve by increasing how hard the tires push against the road via the throttle, engine, and drive train successively.

1. Adapted from Fifth generation Chevrolet Malibu on Interstate 85 in Durham, North Carolina by Ildar Sagdejev (Specious) - Own work, CC BY-SA 3.0, via wikimedia commons

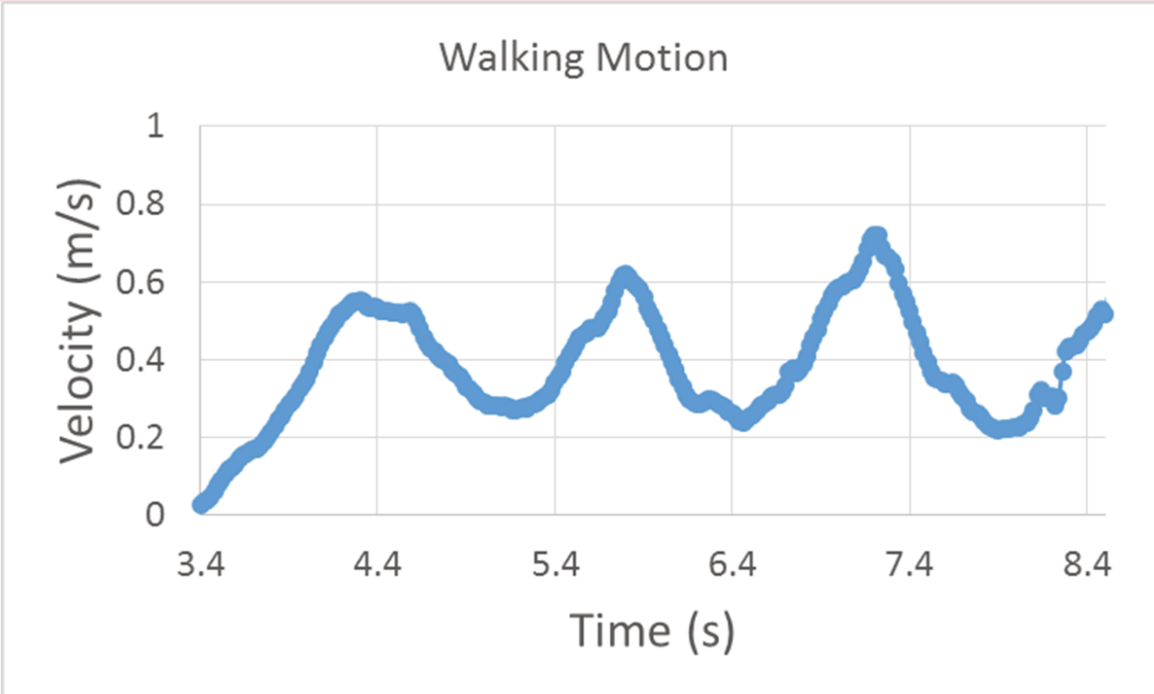
Every Day Examples: Walking and Running

When walking or running you push horizontally against the floor and the floor pushes back, providing you with the net force necessary to create acceleration. Walking at constant average speed is achieved by alternating of forward acceleration caused when the floor pushes forward on your back foot, and backward acceleration caused by the floor pushing back on your front foot. These accelerations average out to zero so velocity appears constant, but if you use a sensor capable of taking several measurements per second, then you can see the oscillatory nature of walking motion:



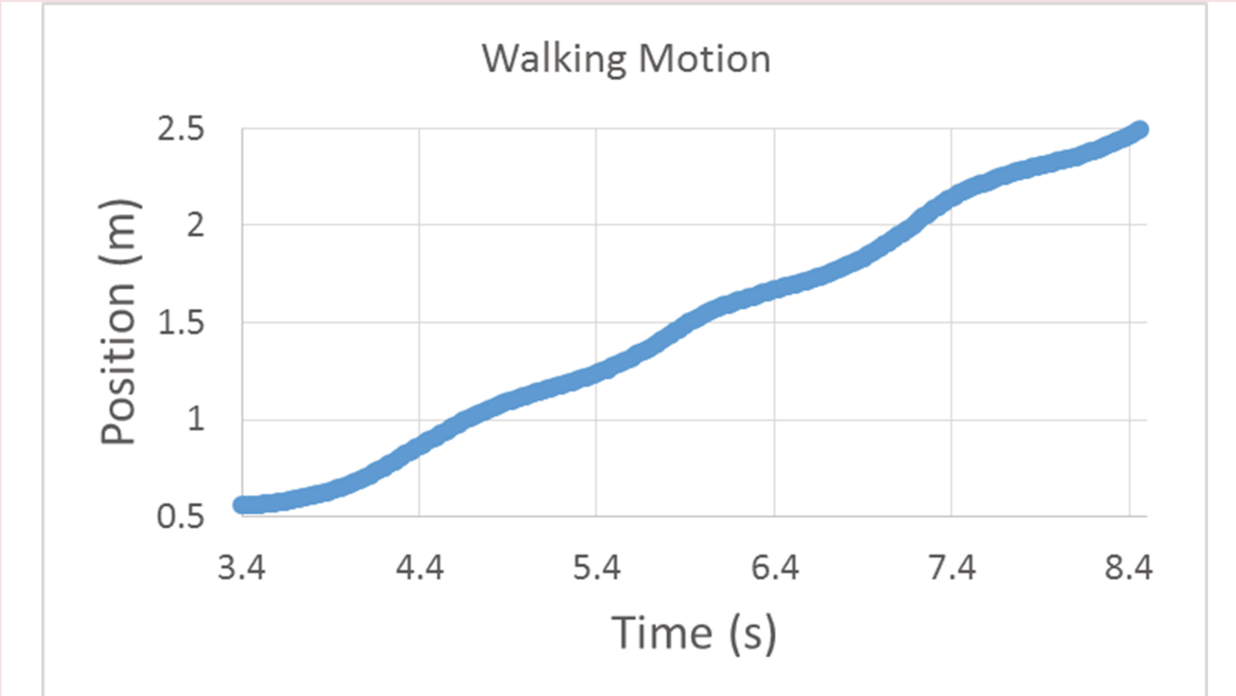
Acceleration vs. time curve for a person walking.

An initial positive acceleration corresponds with the change in velocity away from zero during the first step. Afterward, constant walking motion results in acceleration that oscillates from positive to negative and averages out to zero.



Velocity vs. time curve for a person walking.

The oscillating accelerations result in a velocity that alternates between slowing down and speeding up, however we can see that the velocity stays positive so you are always making progress in the direction you intend to walk. We also see that over a full gait cycle average velocity is constant, near 0.4 **m/s** for this example, which agrees with the zero average acceleration in the previous graph.



Position vs. time curve of a person walking.

As you make progress, the position increases roughly linearly with an average slope equal to your constant average velocity, in this case **0.4 m/s**. However the oscillations in the instantaneous velocity are noticeable as slight variations in the slope of the position graph.

CHAPTER 72.

LOCOMOTION INJURIES

PREVENTING INJURIES

Injuries can be caused by large forces in the absence of acceleration, such as crushing injuries, and those types of injuries can be analyzed using concepts of static equilibrium. However, more often injuries are caused by large forces associated with large accelerations experienced during locomotion. Therefore, we can reduce the likelihood of injuries by:

1. Increasing the ultimate strength of body tissues so that they can handle larger stress and thus larger force.
2. Increasing the cross-sectional area of body parts so that the stress remains below the tissue's ultimate strength, even for larger forces.
3. Decrease the size of forces and resulting stress experienced by the body.

The first two options are controlled by genetics and regular exposure to large, but not injury inducing forces, also known as exercise.[1] The next few chapters will focus on the third option, which is achieved thoughtful movement.

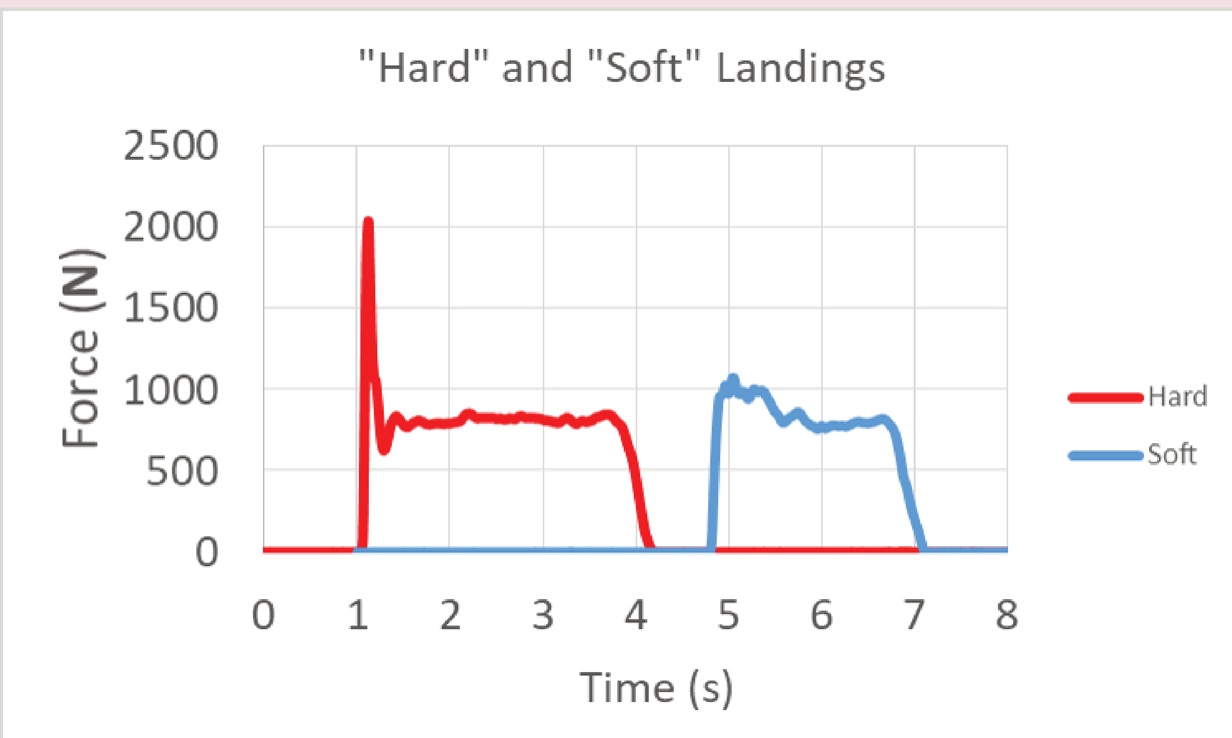
Everyday Examples: Landing after a Jump

You naturally tend to bend your knees when landing after a jump, rather than keep your knees locked and your legs rigid. The reason is that rigid legs bring you to an abrupt stop, but bending your knees allows you to spread the landing out over a longer time, which we have just learned, reduces the average force.

1. Carlson, K. J., & Marchi, D. (2014). *Reconstructing Mobility*. New York: Springer. doi:10.1007/978-1-4899-7460-0

Stiff and bent-leg landings that produced the force vs. time data shown below.

The force vs. time graphs show the normal force applied to a person when landing on one foot after stepping off from a 0.1 **m** height as seen in the previous GIF. The graph on the left was the more rigid leg landing (it didn't feel good) and the graph on the right was a bent-knee landing.



Force vs. time data for a stiff-legged landing (red) and crouching landing (blue).

Notice that the stiff-legged “hard” landing nearly doubled the peak force applied to the body.

When thinking about how to reduce acceleration and the associated forces we should reexamine the definition of average acceleration:

(1) $$\mathbf{a_{ave}} = \frac{\mathbf{\Delta v}}{\Delta t}$$

From the above definitions we see that there are really two options for reducing accelerations. We can reduce the amount that velocity changes, or we can increase the time over which the velocity changes (or both). Of course we could simply stay away from any situation that could lead to large changes in velocity, but then we would have to avoid riding in cars, running, heights, or any situation in which we might trip and fall down. Avoiding large velocity changes all together would not be practical or fun, so we need to make sure those changes happen in a controlled way (slowly). Driving without looking at your phone is a good start.

SOFTENING IMPACTS

Assuming we do experience large changes in velocities, we need to focus on increasing the time over which the velocity changes in order to reduce the average acceleration and average net force. Said another way, *use small net force experienced over a long time to produce the same velocity change as a large net force experienced over a short time.*

Reinforcement Activity

The people in this video are well aware of techniques for reducing forces by extending impact time.

We see from the graph in the previous everyday example that the force varies during an impact and it’s often the peak force that we are really worried about with regard to injury prevention. This complicates the quantitative analysis of our force-reducing strategies, however we recognize that lowering the peak force in turn lowers the average force so we will analyze force-reducing strategies in terms of the average force. We start with our definition for average acceleration:

$$\mathbf{a_{ave}} = \frac{\mathbf{\Delta v}}{\Delta t}$$

Then we can use Newton's Second Law to relate the average acceleration and average force:

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https://openoregon.pressbooks.pub/bodyphysics/?p=1940

$$\frac{\mathbf{F_{ave}}}{m} = \frac{\mathbf{\Delta v}}{\Delta t}$$

Finally we can rearrange the result as needed to solve our problem. For example, if we want to know the time over which to extend an impact to keep the average force below a certain value, we could rearrange to get:

$$\Delta t = m\frac{\mathbf{\Delta v}}{\mathbf{F_{ave}}}$$

Of course we can always expand Δv if it helps us solve a problem:

$$\Delta t = m\frac{\mathbf{v_f} - \mathbf{vi}}{\mathbf{F_{ave}}}$$

Everyday Example: Key Drop

An everyday example in the previous unit helped us to determine that when a friend drops a set of keys to us from 35 **ft** up in their third story apartment, the keys will arrive at 47 **ft/s**, or 14 **m/s**,, or 32 **mph**. We also mentioned that the keys smacking our hands at that speed would hurt, but that we would soon learn about strategies to prevent injury. We have arrived at that point. Now we know what to do: extend the time over which we bring the keys to rest and we will reduce

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the average (and peak) force applied to the keys. By Newton's Third Law, we know that the force on the keys is equal and opposite to the force on our hands, so analyzing the force on the keys tells us about the force on our hand. Let’s get quantitative and approximate the impact time necessary to prevent damage to our hand. We will use the last equation from the text above, which we solved for Δt:

$$\Delta t = m\frac{\mathbf{v_f} - \mathbf{v_i}}{\mathbf{F_{ave}}}$$

To use the above equation we first we need to estimate the force required for the key to break skin. If we placed a key on-edge on top of our hand and someone stood on it, that would likely cause injury. If we instead placed a 5 **lb** textbook on the key it probably would not break the skin, so let’s aim to keep the average force on the keys (and thus our hand) below 5 **lbs**, or 22 **N**. However, we know the peak force could be several times bigger than the average force (see the graph in the previous example), so let’s include a safety factor of 10 and keep the force below 2.2 **N**. Now that we have a force value to work with, we just need a mass for the keys, which would be about 0.050 **kg** as you can see in this video of someone putting a car key on a scale. Now we can enter these values into our equation, being careful about our choice of directions. Let’s say downward is the negative direction so our initial velocity is -14 **m/s** and the upward force on the keys from our hand is positive. Of course the final velocity of the key is zero after we catch them.

$$\Delta t = 0.05\,\mathbf{kg}\frac{0 - (-14\,\mathbf{m/s})}{2.2\,\mathbf{N}} = 0.32\,\mathbf{s}$$

We need to move our hands along with the keys as we catch them to ensure that our “soft catch” lasts for 0.32 **s** (about 1/3 of a second).

CHAPTER 73.

COLLISIONS

COLLISIONS

So far we have analyzed forces applied to the body by the earth during impact after a fall and during locomotion such as walking, jumping, and landing. These events are examples of collisions. Even though we usually use the word collision to refer to objects that were initially separated and came together, in fact any event that involves objects applying force on one another can be considered a collision and analyzed a such. In each of the collision we have analyzed so far we assumed one of the objects (the earth) did not change velocity when it applied force to the body, even though we know from Newton's Third Law that earth felt a force back from the body. This was a reasonable assumption because the earth is so much larger than a human body, but ignoring the motion of the larger object in a collision is not always reasonable. For example, the following GIF shows a basic form of locomotion in which two objects push against one another and separate.

Animated GIF

Sitting in a wheeled chairs, Science Lab Technician Becky Kipperman (left) and Associate Chemistry Professor Sean Breslin (right) push against one another. This collision causes a leftward change in motion for Becky and a smaller rightward change in motion for Sean.

Notice that both objects experienced a noticeable change in velocity, but the velocity changes were not equal in size. In this example, the wheels minimize friction so that the net horizontal force on each person is just the force from the other person. Newton's Third Law tells us that these forces are equal in size, so why does one object experience a greater change in velocity, even though they have the same net force? Newton's Second Law provides the answer: given the same net force, a more massive object will experience a smaller acceleration.

(1) $$\mathbf{a} = \frac{\mathbf{F_{net}}}{m}$$

This effect becomes more apparent when the difference in mass between the objects is greater:

Sitting in a wheeled chairs, Science Lab Technician Becky Kipperman (left) and Associate Chemistry Professor Sean Breslin (right) push against one another while the author is attached to Sean in another chair, but not touching the floor. This collision causes a leftward change in motion for Becky and a much smaller rightward change in motion for Sean and the author. The objects experience equal and opposite changes in momentum though.

The combined mass of Sean and the author is more than 3x the mass of Becky, therefore they experience only 1/3 the change in velocity. This mode of locomotion is really no different from you pushing against the ground when walking. When you push off the ground to walk forward you cause the Earth to move back in return. When you do a push-up, you actually push the Earth down just a little bit. Go you!

MOMENTUM

So far we have been ignoring the change in motion of the earth because the mass of the earth is so large that its change in motion isnegligible. For example, when analyzing impact forces we assumed that the final velocity of the body was zero after a collision with the earth and we used that final velocity to calculate acceleration and then net force. However, when objects of similar mass collide we have to keep track of all objects in the collision, which we call *the system*, because the final velocity of the objects in the system after the collision might not be zero. For example, in this video of a car accident we see that both cars are moving after the collision (they eventually come to rest due to friction, but we can analyze that separately from the collision forces).

To analyze how mass affects changes in velocity during a collision we use the combination of mass times velocity ($m\mathbf{v}$), which is known as the momentum ($\mathbf{p}$). Written in symbol form, the momentum is:

$$(2)\quad \mathbf{p} = m\mathbf{v}$$

CONSERVATION OF MOMENTUM

The Law of Conservation of Momentum states that the combined total momentum of all objects in a system must be the same immediately before and immediately after a collision:

$$(3)\quad \mathbf{p_f} = \mathbf{p_i}$$

If we have only two objects and their masses do not change during the collision we can write the Law of Conservation of Momentum as:

(4) $m_{1,i}\mathbf{v_{1,i}} + m_{2,i}\mathbf{v_{2,i}} = m_{1,f}\mathbf{v_{1,f}} + m_{2,f}\mathbf{v_{2,f}}$

Everyday Example: Locomotion

When analyzing locomotion we have ignored the motion of the earth. Let's verify that to be a reasonable assumption. A person of about 65 **kg** mass starts from rest and takes a step so they have a velocity of 1.2 **m/s** at the end of the step. What is the resulting velocity of the earth? We only have two objects of constant mass (body and earth) so we will use the previous equation:

$$m_{1,i}\mathbf{v_{1,i}} + m_{2,i}\mathbf{v_{2,i}} = m_{1,f}\mathbf{v_{1,f}} + m_{2,f}\mathbf{v_{2,f}}$$

The initial velocity of both objects is zero, (so their initial momenta are also zero):

$$0 + 0 = m_{1,f}\mathbf{v_{1,f}} + m_{2,f}\mathbf{v_{2,f}}$$

Now we subtract the initial momentum of the person (object #2) to the left side:

$$-m_{1,f}\mathbf{v_{1,f}} = m_{2,f}\mathbf{v_{2,f}}$$

Finally we divide by the mass of the earth to isolate the final velocity of the earth:

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$$\frac{-m_{1,f}\mathbf{v_{1,f}}}{m_{2,f}} = \mathbf{v_{2,f}}$$

And switching sides to have the final earth velocity on the left we are ready to enter numbers. We just need to look up the mass of the earth:

$$\mathbf{v_{2,f}} = \frac{-m_{1,f}\mathbf{v_{1,f}}}{m_{2,f}}$$

The mass of the earth is $5.6 \times 10^{24}\,\mathbf{kg}$ so we have:

$$\mathbf{v_{2,f}} = \frac{(-65\,\mathbf{kg})(1.2\,\mathbf{m/s})}{5.6 \times 10^{24}\,\mathbf{kg}} = 1.4 \times 10^{-23}$$

That's a final earth velocity of 14 with 22 zeros in front of it, or about the width of an atom per million years. I think we were justified in neglecting the earth velocity in our analysis so far.

Reinforcement Exercises: Locomotion

Everyday Examples: Collisions

Let's analyze the car accident in the previous video. The initial momentum of the stopped car (car #1) was zero: $\mathbf{p_{1,i}} = 0$. The momentum of the jeep (car #2) was: $\mathbf{p_{2,i}} = m_2\mathbf{v_{2,i}}$. Therefore the total initial momentum was

$$\mathbf{p_i} = 0 + m_2\mathbf{v_{2,i}}$$

The cars lock together immediately after the collision and only separate later so they have the same final velocity immediately after the collision, we'll call it v_f. Sticky collisions like this are known as perfectly inelastic collisions, and for such collisions we can treat the objects moving together as a single object that has their combined total mass. The final momentum is then:

$$\mathbf{p_f} = (m_2 + m_1)\mathbf{v_f}$$

Conserving momentum during the collision tells us to set the initial and final momenta equal:

$$m_2\mathbf{v_{2,i}} = (m_2 + m_1)\mathbf{v_f}$$

If we want to solve this perfectly inelastic collision equation for the final velocity we divide by the combined mass:

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$$\mathbf{vf} = \frac{m_2 \mathbf{v_{2,i}}}{m_2 + m_1}$$

We can look up some data on the cars and find that the length of the Jeep is 3.8 **m**, the mass of the jeep is about 1500 **kg** and a small sports car mass is about 1000 **kg**. [12] Now let's estimate some numbers from the video (a quick method is to use the slo-mo feature on a smartphone to film the video as it plays with a running stopwatch also visible in the frame). We see that before the collision the Jeep covers at least two of its own lengths in about 0.4 **s** so calling its direction the positive, its initial velocity will be:

$$\mathbf{v_{2,i}} = \frac{2 \times 3.8\,\mathbf{m}}{0.4\,\mathbf{s} = 19\,\mathbf{m/s}} = 42\,\mathbf{MPH}$$

We are ready to calculate the final velocity of the jeep-car combination:

$$\mathbf{v_f} = \frac{1500\,\mathbf{kg} \times 19\,\mathbf{m/s}}{1500\,\mathbf{kg} + 1000\,\mathbf{kg}} = 12\,\mathbf{m/s} = 27\,\mathbf{MPH}$$

This is an interesting result, but what's really cool is that if we estimate the collision interval we can calculate the average force applied to each car. From the video the collision time appears to be about 0.5 **s**. Let's do the Jeep first.

We start from Newton's Second Law:

(5) $\mathbf{F_{ave}} = m\mathbf{a} =$

Then write out the acceleration as change in velocity over change in time:

(6) $$\mathbf{F_{ave}} = \frac{m\left(\mathbf{v_f} - \mathbf{v_i}\right)}{\Delta t}$$

We have the final velocity of 12 **m/s** from our previous work using momentum conservation, so we can enter all our values:

(7) $$\mathbf{F_{ave}} = \frac{m\left(\mathbf{v_f} - \mathbf{v_i}\right)}{\Delta t} = \frac{1500\,\mathbf{kg}\left(12\,\mathbf{m/s} - 19\,\mathbf{m/s}\right))}{0.5\,\mathbf{s}} = -23,000\,\mathbf{N}$$

The force on the jeep should be in the negative, just as we found, because we originally chose backward as the negative direction.We known from Newton's Third Law that the -23,000 **N** force on the Jeep from the car is paired with a 23,000 **N** force felt by the car from the Jeep. That's over 5,000 **lbs** of average force on each vehicle, the peak force would be much greater.

Reinforcement Exercise

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1. "2016 Mazda MX-5 Curb Weight Released: Guess How Many Previous Miatas Are Heavier" by ALEXANDER STOKLOSA, Car and Driver
2. "Jeep Wrangler (TJ)" by Wikipedia

CHAPTER 74.

EXPLOSIONS, JETS, AND ROCKETS

EXPLOSIONS

We have found that locomotion can be achieved by collisions consisting of objects in contact being forced apart, similar to the way that pieces of an object separate during an explosion. Explosions must also obey the Law of Momentum conservation. If an object starts at rest, then when we add up the momentum of every piece of the object after the explosion we must end up with zero, just as in the previous examples of collisions with only two "pieces". Watching an explosion in reverse helps to illustrate this point:

After the explosion of the watermelon the total momentum must be zero because it was zero before the explosion. The momentum of pieces moving in any one direction must cancel out the momentum of pieces moving in the opposite direction. Therefore, we see no particular direction that has noticeably more pieces, larger pieces, or faster moving pieces. The explosion is symmetric. (The table does redirect some pieces upward, so the explosion might not appear completely symmetric in the vertical direction.)

If we really pay attention to the watermelon explosion we can see that no pieces move downward because the table redirects them. If we were to actually add up all the momenta of all the pieces we would find that the watermelon system had a net upward momentum. There was an *external* force acting on the system of watermelon pieces and therefore the momentum of the watermelon system was not conserved in this explosion. If we include the table and the earth it's attached to in our system, then the forces between the watermelon pieces and the table are *internal* to our system and we would find that the momentum of that system was conserved. This idea is summarized by the Principle of Momentum Conservation, which states that *whenever the net external force on a system is zero, the momentum of the system will not change*. The Law of Conservation of Momentum is very similar and sort of tells us how to test the principle: *If you include all of the objects involved in a collision, so that there are no external forces from objects outside the system, and you add up the momenta of all those objects before and then again after a collision you will get the same value.*

IMPULSE

When the net external force on a system is not zero, such as for the watermelon, then the momentum will change and the Impulse-Momentum Theorem tells us how:

(1) $\mathbf{p_f} - \mathbf{p_i} = \Delta t \mathbf{F_{ave}}$

We can see that the change in momentum is calculated as initial subtracted from final, similar to changes in velocity, position, time, or any other quantity. The right side of the equation, average force multiplied by the collision time, is known as the impulse (I). The force and resulting impulse on the watermelon system from the table were upward, therefore the momentum of the watermelon system changed from zero to upward.

Exercises

JET PROPULSION

The flyboard in the previous video operates with an externally located pump that shoots water up the hose to the board which re-directs it downward. The momentum of the water was not conserved when it collided with the board, therefore it must have felt an impulse, a.k.a a net force for some amount of time. Newton's Third Law tells us that the board must have felt an equal and opposite force back during that time, and that force balances the weight of the board and rider.

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Everyday Examples

Let's estimate the mass flow rate (mass of water expelled per time) required just to hold up the board and a person. This video is helpful.

The board mass of the board and rider is 93 **kg**, so multiplying by **g** (9.8 **m/s/s**) we get a weight of 911 **N.** The board must apply 911 **N** of downward force on the water in order to receive that same size upward force. The impulse on the water resulting from the downward force will change its momentum according to the impulse-momentum theorem:

$$\mathbf{p_f} - \mathbf{p_i} = \Delta t \mathbf{F_{ave}}$$

Assuming the water moves up the hose, bounces off the board, and exits at the same speed it entered, then the initial water momentum is just the opposite (negative) of the final momentum:

$$\mathbf{p_f} - (-\mathbf{p_f}) = \Delta t \mathbf{F_{ave}}$$

The double negative on the left becomes an addition:

$$2\mathbf{p_f} = \Delta t \mathbf{F_{ave}}$$

We don't have a specific mass of water having a specific collision because the process appears continuous, but we could think image many tiny chunks of water colliding, (even to the point of individual water molecules). We can we write the final momentum of each water chunk in terms of its mass and final velocity:

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$$2m\mathbf{v_f} = \Delta t\mathbf{F_{ave}}$$

Now if we divide each side by two and by the final velocity we can isolate the mass:

$$m = \frac{\Delta t\mathbf{F_{ave}}}{2\mathbf{v_f}}$$

We don't know the Δt for each collision, but we don't need to. Dividing by the time interval will give us the water mass that collides per time interval, which is exactly what we want:

$$\frac{m}{\Delta t} = \frac{\mathbf{F_{ave}}}{2\mathbf{v_f}}$$

Running the video in slow motion I made a very rough estimate of the water exit velocity and found 16 **m/s** downward. We already know the force on the water needs to be 911 **N** downward, so we can enter those values:

$$\frac{m}{\Delta t} = \frac{(911\,\mathbf{N})}{2(16\,\mathbf{m/s})} = 30\,\mathbf{kg/s}$$

The board must redirect 30 **kg** of water each second in order to hold the rider. Water has a density of 1 Liter per **kg**, so 30 liters of water pass through the system each second. You may have noticed that "bouncing the water off the board, instead of just shooting it out like a rocket, reduced the flow rate by half. This is because this "bounce" doubled the impulse on the water (and back on the board). We will talk more about bouncy collisions in the next chapter.

ROCKET LOCOMOTION

Some machines actually use real chemical explosions for locomotion. For example, rocket fuel burns to produce hot, rapidly expanding gas which shoots out of the rocket backward, providing an impulse on the rocket. The force associated with that impulse is known as *thrust*. The analysis we used for the fly board doesn't really work for the rocket because the mass of the rocket changes as it burns fuel, but that analysis is very interesting and you should ask your instructor about it.

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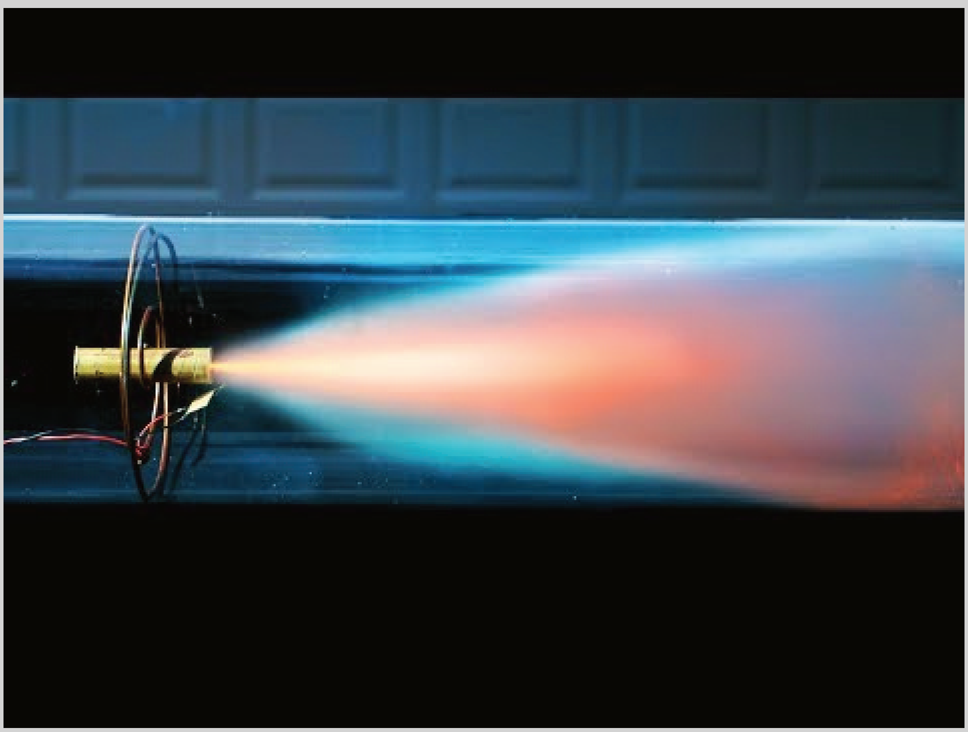

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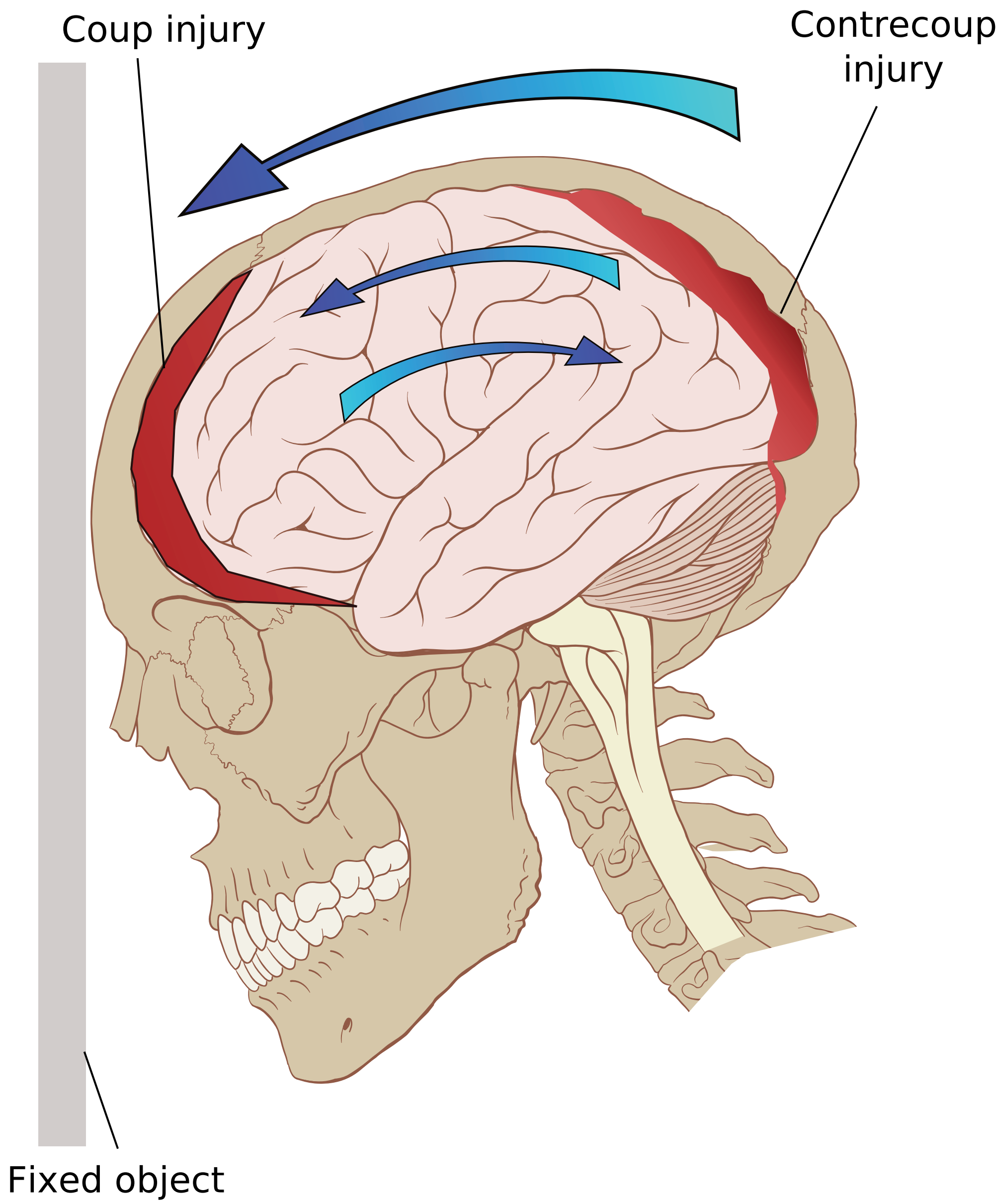
CHAPTER 75.

SAFETY TECHNOLOGY

BOUNCE IS BAD

If the skull impacts a hard surface, but neither the skull or surface are significantly deformed, then the skull will bounce back. This type of collision is not perfectly inelastic because the skull did not stick to the surface. In this case the relative impact speed between the still-forward moving brain and the backward moving skull is nearly twice what it would have been if the skull had simply stopped.



The alternating accelerations of the skull and the inertia of the brain combine to cause impacts on opposing sides of the brain during a coup contrecoup injury. Image credit: Contrecoup by Patrick J. Lynch, medical illustrator via Wikimedia Commons

1

After the bounce, as the neck causes the skull to slow down on the way backward, the inertia of the brain may lead to a second impact on the back of the brain, as illustrated in the previous image. Aside from an additional brain tissue injury, the combined swelling of the two opposed injuries will put amplify the pressure on the brain and increase the likelihood of permanent injury. This type of

1. Contrecoup by Patrick J. Lynch, medical illustrator [CC BY 2.5 (https://creativecommons.org/licenses/by/2.5), GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons

injury is known as a *Coup Countrecoup* , or translated from French by Google Translate, *blow, counter blow*.

AIR BAGS

Everyday Example: Airbags

Check out this video of crash-testing with and without airbags.

https://youtu.be/NACA1W2A5Wk

During the crash the driver's head starts out with the same velocity as the car. The airbag increases the time it takes for the head to come to rest, which will decrease the force on the head. In order make sure the head does actually come to rest instead of bouncing the airbag has vents that allow air to be pushed out during impact so it deflates instead of staying completely full and keeping its shape.

The impulse-momentum theorem introduced in the previous chapter will help us to analyze technology designed to minimize the forces on your the body:

(1) $\mathbf{p_f} - \mathbf{p_i} = \Delta t \mathbf{F_{ave}}$

If we divide over the time, we see that there are two options for reducing the force on the body during a collision; you can maximize collision time, or minimize the change in momentum, or both:

(2) $\dfrac{\mathbf{p_f} - \mathbf{p_i}}{\Delta t} = \mathbf{F_{ave}}$

Through our analysis of locomotion, falling, and landing we have already examined strategies for increasing the collision time, but how do we actually reduce change in momentum you experience during a collision? Prevent the bounce! Let's examine why the bounce is bad using an the airbag example. First we write the momentum of the head in terms of its mass and velocity.

(3) $\dfrac{m\mathbf{v_f} - m\mathbf{v_i}}{\Delta t} = \mathbf{F_{ave}}$

If the collision is perfectly inelastic so the head does not bounce at all, then final velocity is zero:

(4) $-m\mathbf{v_i}\Delta t = \mathbf{F_{ave}}$

We see that the force on the head depends on the head mass, the initial velocity, and the collision time.

If instead the head bounces back at the same speed it went in (image the airbag was a rubber ball), then the final velocity is just equal and opposite (negative) the initial velocity:

(5) $\dfrac{m(-\mathbf{v_i}) - m\mathbf{v_i}}{\Delta t} = \mathbf{F_{ave}}$

The left side can be combined:

(6) $\dfrac{-2m\mathbf{v_i}}{\Delta t} = \mathbf{F_{ave}}$

That is twice the force compared to when the head just came to rest! If the head were to bounce back, but not at full speed, then the force would still be greater than the perfectly inelastic case, but not twice as great.

Reinforcement Exercises

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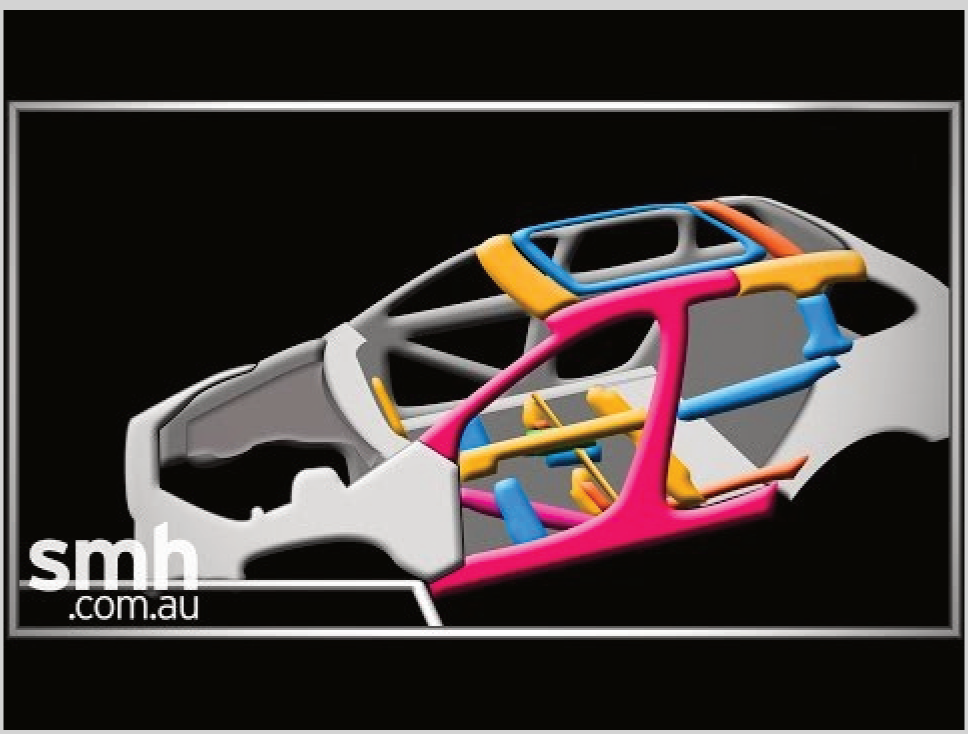
CHAPTER 76.

CRUMPLE ZONES

KINETIC ENERGY

Crumple zones built into modern cars also serve the purpose of reducing force by increasing the collision time and minimizing bounce. Crumple zones cause cars to be totaled more often, but cars can be replaced and people can't be. Notice that the presenter in the previous video isn't talking about impulse or momentum, but he does keep mentioning absorbing energy. This energy that he is claiming will be absorbed by the crumple zone is the energy stored in the motion of the car. Any



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moving object has this type of energy, known as kinetic energy (*KE*). The amount of kinetic energy an object has depends on its mass and its speed:

(1) $$KE = \frac{1}{2}mv^2$$

Notice that the kinetic energy depends on speed, but not velocity because *KE* doesn't have a direction (an object can't have negative KE). Even if we input a negative velocity into the KE equation, it gets squared so *KE* would come out positive anyway. The SI unit of kinetic energy is a **Nm**, which has it own name, the Joule (*J*).

Reinforcement Activity

ELASTIC POTENTIAL ENERGY

During the collision the car materials were compressed by the wall. If the stress remained below the yield points of the materials, so they were remained in the elastic region, then the kinetic energykinetic energy from the car would have been transferred into elastic potential energy stored in the compression of the materials. This stored energy has the potential to become kinetic energy, which is exactly what would happens when the materials then spring back causing the car to "bounce" back from the wall.

Reinforcement Exercise

If the car had bounced back at the same speed that it had entering the collision, then the final kinetic energy would be the same as the initial, and we would say that kinetic energy had been conserved. Collisions that conserve kinetic energy are known as elastic collisions. Collisions that don't are known as inelastic collisions. In the previous chapter we learned that bounce was bad when it comes

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to minimizing the force on the body during a collision. The purpose of crumple zones is to ensure that very little of the kinetic energy remains after the collision by making them very inelastic. The key to accomplishing that is to ensure that kinetic energy is transferred into thermal energy instead of elastic potential energy by designing the materials to break instead of bounce.

THERMAL ENERGY

If you watch the video carefully, you see that the car was moving forward, then for a moment it was stopped and thus had zero kinetic energy, and then it was moving backward (though not as fast), so once again it had kinetic energy. Some of the original kinetic energy was stored as elastic potential energy and then released as kinetic energy again, but most of it was not. If you are wondering where that energy went, then you are was very perceptive, because in fact the Principle of Conservation of Energy tells us that *energy cannot be created or destroyed, only transferred from one form to another and/or one object to another, via work.*

The force applied to the materials during the collision caused a stress on the materials. Some materials were stressed above their ultimate strength so they fractured. Some other materials didn't fracture, but were stressed beyond their elastic limit and into their plastic region so that they were permanently deformed. In either case, the work done to deform the materials transferred kinetic energy into thermal energy, effectively slowing the car down, but warming it up. Crumple zones are designed to deform permanently in order to convert kinetic energy into thermal energy.

Reinforcement Exercises

MICROSCOPIC KINETIC ENERGY

Now that we have introduced thermal energy as a new type of energy, we will reverse course and say that thermal energy is not actually a new type of energy, but rather just kinetic energy on a microscopic scale. Thermal energy is the energy stored in the motion of atoms and molecules that make up a material. Transferring thermal energy to a system really just means that you caused it's atoms and molecules to move faster. The work done in compressing objects past their elastic limit and the work done by kinetic friction will always transfer some energy into thermal energy. You can visualize this microscopic process for kinetic friction using the simulation below.

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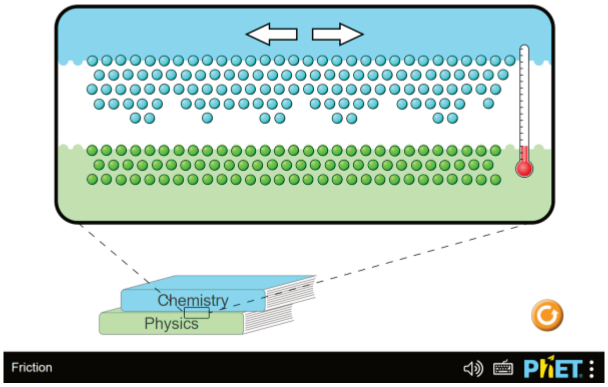

COEFFICIENT OF RESTITUTION

The relative elasticity of collisions is defined by the coefficient of restitution (COR) which relates the final kinetic energy and the initial kinetic energy. For a moving object striking a stationary object that doesn't move, as in the crumple zone video, the COR is calculated as final speed divided by initial speed.

$$COR = \sqrt{\frac{KE_f}{KE_i}} = \sqrt{\frac{1/2mv_f^2}{1/2mv_i^2}} = \frac{final\ speed}{initial\ speed} \quad (2)$$

A perfectly elastic collision would have a COR of one. If any materials are permanently deformed during a collision then you can be sure the collision was not perfectly elastic. In fact, perfectly elastic collisions don't really occur, but many situations come very close and we can approximate them as perfectly elastic.

Check out this simulation that allows you to visualize different types of collisions.

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CHAPTER 77.

UNIT 8 REVIEW

Key Terms and Concepts

Inertia

Locomotion

Newton's Second Law

Newton's Third Law

Perfectly Inelastic Collision

Law of Conservation of Momentum

Impulse-Momentum Theorem

Kinetic Energy

Elastic Potential Energy

Thermal Energy

Learning Objectives

1. Describe how locomotion occurs in terms of Newton’s Laws of Motion.[2]
2. Apply Newton’s Second and Third Laws of motion to analyze the motion of objects.[3]
3. Apply the Law of Conservation of Momentum to analyze the motion of objects.[3]
4. Evaluate and explain strategies for reducing the forces experienced by objects undergoing collisions.[2]

CHAPTER 78.

UNIT 8 PRACTICE AND ASSESSMENT

Outcome 1

1) An asteroid speeds through space, distant enough from anything else to be essentially unaffected by gravity. Will the asteroid slow down because it has no power system to provide a force on it? Explain?

2) Does your car slow down when you take your foot off the gas? Compare and contrast this situation to the previous one involving the asteroid and *explain* the similarities or differences in the outcome.

Outcome 2

3) Imagine you are being chased by a horde of zombies across the frozen wasteland of a post-apocalyptic Northwest United States. You attempt to lose the zombies by running across a frozen pond.

a) What is the normal force the ice must supply to your foot in order to hold you up?

b) You are afraid of breaking through the ice, so you don't want to apply any more normal force than you calculated above. What is the maximum possible force your foot can apply to the ice horizontally without slipping. Cite your source for the necessary friction coefficient between ice and shoes.

c) If you take 3 steps, with each step putting your foot in contact with the ice for 0.30 **s** and apply the force you found above, what is the total impulse you apply to the ice?

d) What is the total impulse you received from the ice? How do you know?

e) How fast will you be moving after these three steps? [Hint: Use your previous answer and the definition of momentum].

Outcome 3

4) As you near the edge of the pond moving at 4.0 **m/s** on the ice and a zombie is behind you moving at 3.0 **m/s** when a helpful survivor like yourself throws you something to defend yourself with. It has a 11 **kg** mass and a pretty much horizontal velocity of 5.0 **m/s** in the direction opposite to your motion when it reaches you.

a) If you were to catch the weapon, what would your new speed be after catching it? Use your own mass in answering the question. Don't forget to include the initial momentum of both objects in your analysis and be careful about directions.

b) Should you catch the weapon? (Would you still be moving faster than the 3.0 **m/s** zombie after catching it?)

Outcome 4

5) Catching or avoiding the weapon that was thrown to you causes you to slip and fall. Provide some strategies for landing that will minimize the likelihood that you break through the ice. Be specific about how you will move your body and explain your strategy using in terms of Newton's Laws of Motion or the impulse-momentum theorem, elastic and inelastic collisions, the relation between force and stress, and the definition of ultimate strength.

PART IX.

UNIT 9: POWERING THE BODY

Learner Outcomes

1. Define, recognize, and differentiate work, kinetic energy, and potential energy, including elastic, gravitational, and chemical.[2]
2. Apply the Law of Conservation of Energy and The First Law of Thermodynamics to the analysis of physical processes.[3]
3. Determine the efficiency of physical processes and machines.[3]
4. Evaluate the power output of machines.[3]

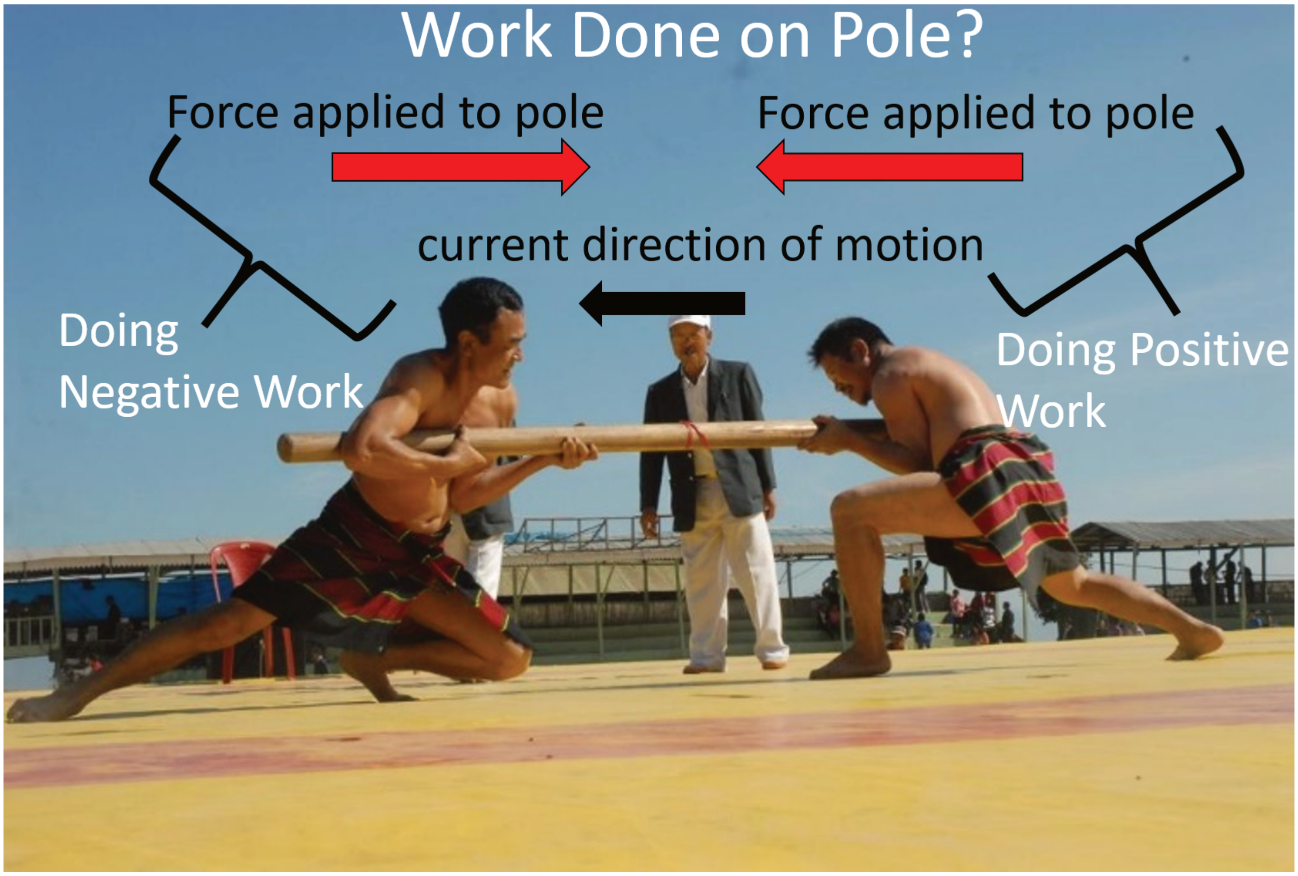
CHAPTER 79.

DOING WORK

We started the previous unit with a discussion of Jolene's motion during a shift on the medical floor of a hospital, including all the starts and stops that she makes. When Jolene is standing still she has zero kinetic energy. As she takes a step to begin walking she now has kinetic energy. Jolene had to supply that energy from within herself. When Jolene comes to a stop her kinetic energy is transferred to thermal energy by friction. When she begins walking again she will need to supply the new kinetic energy all over again. Even if Jolene walks continuously, every step she takes involves two inelastic collisions (the push-off and the landing) so kinetic energy is constantly being transferred to thermal energy. To stay in motion Jolene has to re-supply that kinetic energy. Walking around all shift uses up Jolene's stored energy and that is why she gets tired.

WORK

The amount of energy transferred from one form to another and/or one object to another is called the work. *Doing work* is the act of transferring that energy. Doing work requires applying a force over some distance. The sign of the work done *on* an object determines if energy is transferred *in* or *out* of the object. For example, the athlete on the right is doing positive work on the pole because he is applying a force in the same direction as the pole's motion. That will tend to speed up the pole and increase the kinetic energy of the pole. The athlete on the left is doing negative work on the pole because the force he applies tends to decrease the energy of the pole.



Insuknawr, or Rod Pushing Sport is an indigenous game of Mizoram, one of the North Eastern States of India. A force applied in the same direction as an objects motion does positive work. A force applied in the opposite direction to motion does negative work. Image adapted from from Insuknawr (Rod Pushing Sport) by H. Thangchungnunga via Wikimedia Commons

[1]

The positive or negative sign of the work refers to energy transferring in or out of an object rather than to opposite directions in space so work is not a vector and we will not make it bold in equations.

CALCULATING WORK

The actual amount of work done is calculated from a combination of the average force and the distance over which it is applied, and the angle between the two:

(1) $W = Fdcos\theta$

Everyday Example: Lifting a Patient

Jolene works with two other nurses to lift a patient that weighs 867 **N** (190 **lbs**) a distance of 0.5 **m** straight up. How much

1. Adapted from Insuknawr (Rod Pushing Sport by H. Thangchungnunga [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0) or GFDL (http://www.gnu.org/copyleft/fdl.html)], from Wikimedia Commons

work did she do? Assuming Jolene lifted 1/3 of the patient weight, she had to supply an upward force of 289 **N**. The patient also moved upward, so the angle between force and motion was 0°. Entering these values in the work equation:

$$W = Fdcos\theta = (289\,\mathbf{N})(0.5\,\mathbf{m})cos(0^{\circ}) = 144\,\mathbf{Nm}$$

We see that work has units of **Nm**, which are called a Joules (**J**). Work and all other forms of energy have the same units because work is an amount of energy, but work is not a type of energy. When calculating work the $costheta$ accounts for the force direction so we only use the size of the force (*F*) in the equation, which is why we have not made force bold in the work equation.

The $cos\theta$ in the work equation automatically tells us whether the work is transferring energy into or out of a particular object:

1. A force applied to an object in the opposite direction to its motion will tend to slow it down, and thus would transfer kinetic energy out of the object. With energy leaving the object, the work done on the object should be negative. The angle between the object's motion and the force in such a case is 180° and $cos(180^{\circ}) = -1$, so that checks out.
2. A force applied to an object in the same direction to its motion will tend to cause it to speed up, and thus would transfer kinetic energy in to the object. With energy entering the object, the work done on the object should be positive. The angle between the object's motion and the force in such a case is 0° and $cos(0^{\circ}) = 1$ so that also checks out.
3. Finally, if a force acts perpendicular to an objects motion it can only change its direction of motion, but won't cause it to speed up or slow down, so the kinetic energy doesn't change. That type of force should do zero work. The angle between the object's motion and the force in such a case is 90° and $cos(90^{\circ}) = 0$ so once again, the $cos\theta$ in the work equation gives the required result. For more on this particular type of situation read the chapter on weightlessness at the end of this unit.

The work equation gives the correct work done by a force, no matter the angle between the direction of force and the direction of motion, even if the force points off at some angle other than 0°, 90°, or 180°. In such a case, some part of the force will be doing work and some part won't, but the $cos\theta$ tells us just how much of the force vector is contributing to work.

Reinforcement Exercises

Reinforcement Exercises

[2]

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2. Image and associated practice problem were adapted from "This work" and by BC Open Textbooks is licensed under CC BY 4.0

CHAPTER 80.

JUMPING

WORK-ENERGY PRINCIPLE

How do we calculate the total work when more than one force acts on an object as it moves, so that each force is doing work? What if the forces point in opposite directions so one does positive work and the other does negative work? In this case we calculate the net work done by each force and add them up (keeping negative works as negative) to get the net work. Alternatively, add up the forces, including directions, to find the size and direction of the net force and then multiply by the distance over which the net force is applied to get the net work. Either way will give you the same answer, which will be the net work. The net work tells us how much energy is transferred into or out of the kinetic energy, causing a change in kinetic energy (ΔKE). Everything we have discussed so far can be summed up by the work-energy principle: *The change in kinetic energy of a system is equal to the net work on the system*, or written as an equation:

(1) $W_{net} = \Delta KE$

Alternatively,

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

or in terms of the net force:

(3) $F_{net,ave}dcos\theta = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$

Everyday Examples: Jumping

During a jump a person's legs might apply a force of 1200 **N** upward on their center of mass while the center of mass moves 0.3 **m** upward. Let's figure out what their launch velocity and hang-time will be if the person has a weight of 825 **N**.

First we calculate the work done by their legs.

$$W_L = (1200\,\mathbf{N})(0.3\,\mathbf{m})cos(0^\circ) = 360\,\mathbf{J}$$

Gravity was acting on them during the launch phase as well, so we need to calculate the work done by gravity, which acts in the opposite direction to motion ($\theta = 180):

$$W_g = (825\,\mathbf{N})(0.3\,\mathbf{m})cos(180^\circ) = -247.5\,\mathbf{J}$$

Adding up the works to get the net work:

$$W_net = -247.5\,\mathbf{J} + 360\,\mathbf{J} = 112.5\,\mathbf{J}$$

The work-energy principle tells us to set the change in kinetic energy equal to the net work. We will keep in mind that they started at rest, so the initial kinetic energy was zero.

$$112.5\,\mathbf{J} = \frac{1}{2}mv_f^2 - 0$$

We isolate the final velocity at the end of the launch phase (as the person leaves the ground)

$$\frac{2(112.5\,\mathbf{J})}{m} = v_f^2$$

We can see that we need the persons mass. We just need to divide their weight by *g* = 9.8 **m/s/s** to find it:

$$m = \frac{825\,\mathbf{N}}{9.8\,\mathbf{m/s}} = 84.2\,\mathbf{kg}$$

We insert the mass:

$$\frac{2(112.5\,\mathbf{J})}{84.2\,\mathbf{kg}} = v_f^2$$

Finally we take the square root of the result to find the final velocity:

$$v_f = \sqrt{\frac{2(112.5\,\mathbf{J})}{84.2\,\mathbf{kg}}} = 1.6\,\mathbf{m/s}$$

Reinforcement Exercises

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CHAPTER 81.

SURVIVING A FALL

MECHANICAL ENERGY

When you do work to lift an object and then release it, the energy converts back to kinetic energy as the object falls. This process appears similar to the storage and release of elastic potential energy that we learned about in the previous unit and suggests that we define a gravitational potential energy (PE_g). It's not obvious where gravitational potential energy is stored, but for our purposes can treat it as being stored within the system comprised of the Earth and an object that has been raised. The elastic potential energy, gravitational potential energy and kinetic energy are forms of mechanical energy. Forces and corresponding work that convert mechanical energy from one form to another are known as conservative forces and conservative work. We introduce these new terms because there are many cases when only conservative forces are acting and so energy just transfers between the various forms of mechanical energy within the system. For such cases, any increase in potential energy is offset by a decease in kinetic energy and *vice versa*, so we know $\Delta PE + \Delta KE = 0$. Non-conservative forces do work that converts between mechanical energy, thermal energy, or chemical potential energy (we will learn more about chemical potential energy soon). Friction, drag force, air resistance, forces caused by muscular contractions, and any forces applied by materials as they are permanently deformed are examples of non-conservative forces.

Reinforcement Exercises

Check out this simulation, which shows how energy is transferred among different types.

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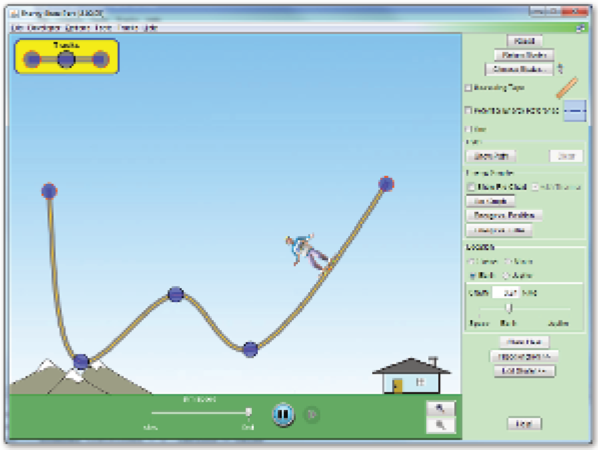

CONSERVATION OF ENERGY

Considering the Principle of Conservation of Energy, we expect that any change to the total energy of a system must be provided by work on the system from the outside (W_{on}). Our observations have confirmed this expectation and are summarized by the Law of Conservation of Energy:

(1) $W_{on} = \Delta KE + \Delta PE + \Delta TE$

Conservative forces between objects in the system do work to convert energy between mechanical types within the system. Non-conservative forces work to convert energy between mechanical energy and other forms within the system, such as thermal energy (TE) and chemical potential energy. In order to increase the total energy of the system, positive work must be done on the system from the outside.

GRAVITATIONAL POTENTIAL ENERGY

According to the Law of Conservation of Energy, if we do work to lift an object farther from the Earth without increasing its kinetic energy or thermal energy we must have increased the gravitational potential energy by the same amount as the work. The force we need to apply is the object's weight, or ($mass \times g$) and the distance we over which we apply the force is the change in height Δh. Therefore the work we did was: $W = mg\Delta h$ and this must be the same the amount that we have changed the gravitational potential energy.

(2) $\Delta PE_g = W_{on} = Fd = mg\Delta h$

Note that the previous equation automatically gives a decrease in gravitational potential energy when an object gets lower because the change in height will be negative. The work done to lift an object is an example of useful work, or work done by the body on the external environment.[1]

1. OpenStax, College Physics. OpenStax CNX. May 13, 2019 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@16.4

Reinforcement Exercises

Everyday Example: Rock Climbing Fall

A rock climber is 3.5 **m** above their last anchor point and fall. They will fall back 3.5 **m** back to the anchor point and then another 3.5 **m** below it before the rope comes tight for a total fall distance of 7.0 **m** (there was 3.5 **m** of rope out when they fell, so they will have to end up hanging by 3.5 **m** of rope). Neglecting air resistance, how fast will they be moving when the rope begins to come tight?

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We will apply the Law of Conservation of Energy during the fall.

(3) $W_{on} = \Delta KE + \Delta PE + \Delta TE$

Neglecting air resistance there are no forces other than gravity on the person during the fall, so only conservative forces are acting and we know mechanical energy is conserved):

(4) $0 = \Delta KE + \Delta PE + 0$

Next we write out the changes in each type of energy:

(5) $0 = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2 + mg\Delta h$

We recognize the initial speed was zero at the start of the fall and that we can divide every term in our equation by mass mass to cancel it out:

(6) $0 = \frac{1}{2}v_f^2 - 0 + g\Delta h$

Then we isolate the speed:

(7) $v_f^2 = 2g\Delta h$

Finally we take the square root:

(8) $v_f = \sqrt{2g\Delta h}$

The climber fell 7.0 **m**, so the change in height was actually -7.0 **m.** We are ready to calculate the final speed:

(9) $v_f = \sqrt{2(9.8, \mathbf{m/s})7, \mathbf{m}} = 11.7, \mathbf{m/s}$

Reinforcement Exercises

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CHAPTER 82.

POWERING THE BODY

CHEMICAL POTENTIAL ENERGY

We have learned that when you jump, bend a paper clip, or lift an object you transfer kinetic energy, potential energy, or thermal energy to the objects, but where did that energy come from and what form was it in before? The energy was stored as chemical potential energy in specific bonds within molecules in your muscle cells, specifically *ATP* molecules. We should note that chemical potential energy is stored in the separation electrically charged particles that make up atoms, analogous to the way gravitational potential energy is stored in the separation of masses. Therefore chemical potential energy is actually just a form of electrical potential energy, but we will not cover the details of electrical potential energy in this textbook, so we will talk about chemical potential energy as its own distinct type of energy.

THE BIOLOGICAL ENERGY CASCADE

The chemical potential energy stored in bonds within ATP is released to do work on muscle fibers (Actin and Myosin) and then work must be done to reform those bonds. That work is done during the ATP cycle shown in the following animation:

The energy to power the ATP cycle is transferred out of chemical potential energy in glucose molecules during cellular respiration. Those glucose molecules entered your body through the food you ate, and ultimately, the chemical potential energy they stored was transferred from electromagnetic energy in sunlight by plants via photosynthesis. [1]. To learn more about these processes consider taking courses in human anatomy and physiology, general biology, cell biology, molecular biology, and biochemistry.

Everyday Example: No work and all heat

Hold an object up in the air. Keep holding. Do you eventually get tired? Why? You are certainly applying a force, but the object hasn't moved any distance, so it would appear that you really done anywork. Why should you get tired when you aren't doing any work? The animation in the previous video provides the answer, you haven't done any useful work, but you have work on a microscopic scale to transfer chemical potential energy to thermal energy. The ATP cycle occurs repeatedly

1. OpenStax College, Biology. OpenStax CNX. Feb 25, 2016 http://cnx.org/contents/185cbf87-c72e-48f5-b51e-f14f21b5eabd@9.92.

just maintain muscle tension, even if the muscle does not actually move a noticeable distance. The ATP cycle continues to use up chemical potential energy even if you aren't doing any useful work. Where does that energy go? Into thermal energy. If you hold the object long enough, you might even begin to sweat! If using stored energy without doing useful work seems pretty inefficient, you're right. In fact the efficiency of the body in such a situation is zero! The next chapter will discuss the efficiency in greater detail.

ELASTIC POTENTIAL ENERGY IN THE BODY

There are biochemical limits on how quickly your body can break down ATP to release chemical potential energy, which limits the rate at which your body is able to do work, also known as power (*P*). For example, making a change in speed changes your kinetic energy, which requires work. Quick changes in speed require the work to be done in short time interval, which equates to a high power output. You can apply some strategies to overcome biochemical power limitations in the short term by storing elastic potential energy in tissue tension and timing the release of that energy. For example you can store elastic potential energy in your Achilles tendon when you squat down before jumping, then release that energy during the launch phase of a jump. However, your body isn't able to store this elastic energy potential energy for long before it changes to thermal energy in the tendon as the fibers reconfigure, so it only provides short-term enhancements to power output.

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Other animals have adapted to store elastic potential energy for longer periods. Dr. Shelia Patek, Chair of the Biomechanics Division at the Society for Integrative and Comparative Biology, discovered that the mantis shrimp has doubled down on the elastic potential energy strategy by using a "structure in the arm that looks like a saddle or a Pringle chip. When the arm is cocked, this structure is compressed and acts like a spring, storing up even more energy. When the latch is released, the spring expands and provides extra push for the club, helping to accelerate it at up to 10,000 times the acceleration [caused by the] force of gravity on Earth [alone]."[2]

QUANTIFYING ELASTIC POTENTIAL ENERGY

We often model particular tissues or other material as a springs, so elastic potential energy is sometimes used interchangeably with *spring potential energy*. The amount of elastic potential energy you can store in a spring can be calculated from the spring constant (*k*) and displacement Δx according to Hooke's Law:

(1) $$PE_E = \frac{1}{2}k(\Delta x)^2$$

A YouTube element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=2187

2. "The Mantis Shrimp Has the World's Fastest Punch" by Ed Yong, Science and Innovation, National Geographic

Everyday Example:

How much elastic potential energy is stored in the Achilles tendon during the crouch phase of a jump?

In the *Modeling Tissues as Springs* chapter of Unit 7 we estimated the typical spring constant of the Achilles tendon to be $8.1 \times 10^6 \ \frac{\mathbf{N}}{\mathbf{m}}$. During a jump the tendon may experience strain of more than 0.06, or 6 **%**.[3] We can use our equation for elastic potential energy above, but first we need to find the stretch distance corresponding to that strain value for a typical Achilles tendon length of 0.15 **m**. Starting with the strain equation:

$$Strain = \frac{\Delta x}{L_0}$$

Rearranging for the stretch distance (displacement):

$$\Delta x = L_0 \times strain = (0.15\,\mathbf{m})(0.06) = 9 \times 10^{-3}\,\mathbf{m}$$

We can now calculate the elastic potential energy stored in the tendon during a jump:

$$PE_E = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2}\left(8.1 \times 10^6\,\frac{\mathbf{N}}{\mathbf{m}}\right)(9 \times 10^{-3}\,\mathbf{m})^2 = 324\,\mathbf{J}$$

Using the equation for a change in gravitational potential energy we find out that the stored elastic potential energy is enough energy to launch a 65 **kg** person an additional 0.5 **m** into the air.

$$PE_g = mg(\Delta h) = (65\,\mathbf{kg})\,(9.8\,\mathbf{m/s})(0.5\,\mathbf{m}) = 319\,\mathbf{J}$$

Storing elastic potential energy in tissues for timed release in parallel with muscle contraction can significantly increase the power output during a jump.

Reinforcement Exercises

POWER

We have seen that storage and time release of elastic potential energy can improve short term power output, or work done per unit time. The power for any energy conversion process can be calculated as:

An interactive or media element has been excluded from this version of the text. You can view it online here:

https://openoregon.pressbooks.pub/bodyphysics/?p=2187

3. "Achilles tendon material properties are greater in the jump leg of jumping athletes" by Bayliss, A. J., Weatherholt, A. M., Crandall, T. T., Farmer, D. L., McConnell, J. C., Crossley, K. M., & Warden, S. J., National Library of Medicine, U.S. National Institutes of Heatlh

$$P = \frac{work}{\Delta t}$$

Power has units of **J/s**, also known as Watts (**W**). Another common unit for power is horsepower (**hp**). There are 746 **W** per **hp**.

Reinforcement Exercises

Everyday Examples: Power Plants

Power plants convert energy from one form to another. The most common type convert chemical potential energy into thermal energy via combustion, and then convert thermal energy stored in steam, and then into kinetic energy via turbines. A large power plant might have an output of 500 million Watts, or 500 **MW**.

When you receive a power bill in the U.S. the typical unit you are billed for is kiloWatt-hours **(kW-hr**). These units can be confusing because we see Watt and think power, but this is actually a unit of energy. This makes sense because you should be billed based on the energy you used, but let's break down the confusing units.

Power is energy divided by time, so a power multiplied by a time is an energy:

$$Power \times \Delta t = \frac{energy\, converted}{\Delta t} \times \Delta t$$

The issue here is we a mixing time units, specifically hours and the seconds that are inside Watts. The reason might be that customers can better relate to **kW-hr** than joules when thinking about their energy usage. For example, leaving ten 100 **W** light bulbs on for one hour would be one **kW-hr** of energy:

$$(10\, bulbs)\frac{100\,\mathbf{W}}{bulb}(1\,\mathbf{hr}) = 1000\,\mathbf{W\dot{h}r} = 1\,\mathbf{kW\dot{h}r}$$

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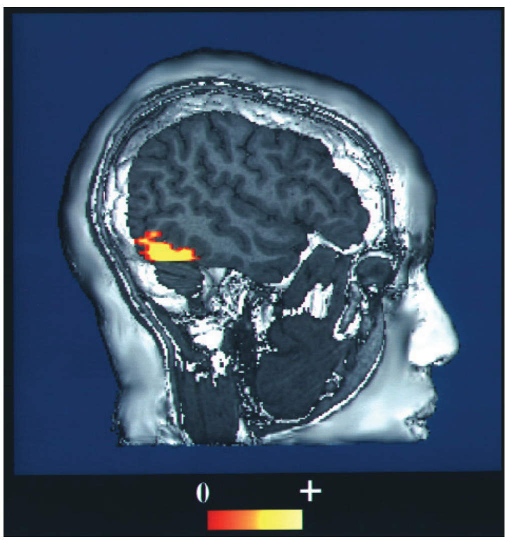
CHAPTER 83.

EFFICIENCY OF THE HUMAN BODY

THE ENERGETIC FUNCTIONS OF THE BODY[1]



This fMRI scan shows an increased level of energy consumption in the vision center of the brain. Here, the patient was being asked to recognize faces. Image credit: NIH via Wikimedia Commons

All bodily functions, from thinking to lifting weights, require energy. The many small muscle actions accompanying all quiet activity, from sleeping to head scratching, ultimately become thermal energy, as do less visible muscle actions by the heart, lungs, and digestive tract. The *rate* at which the body uses food energy to sustain life and to do different activities is called the metabolic rate. The total energy conversion rate of a person *at rest* is called the basal metabolic rate (BMR) and is divided among various systems in the body, as shown the following table:

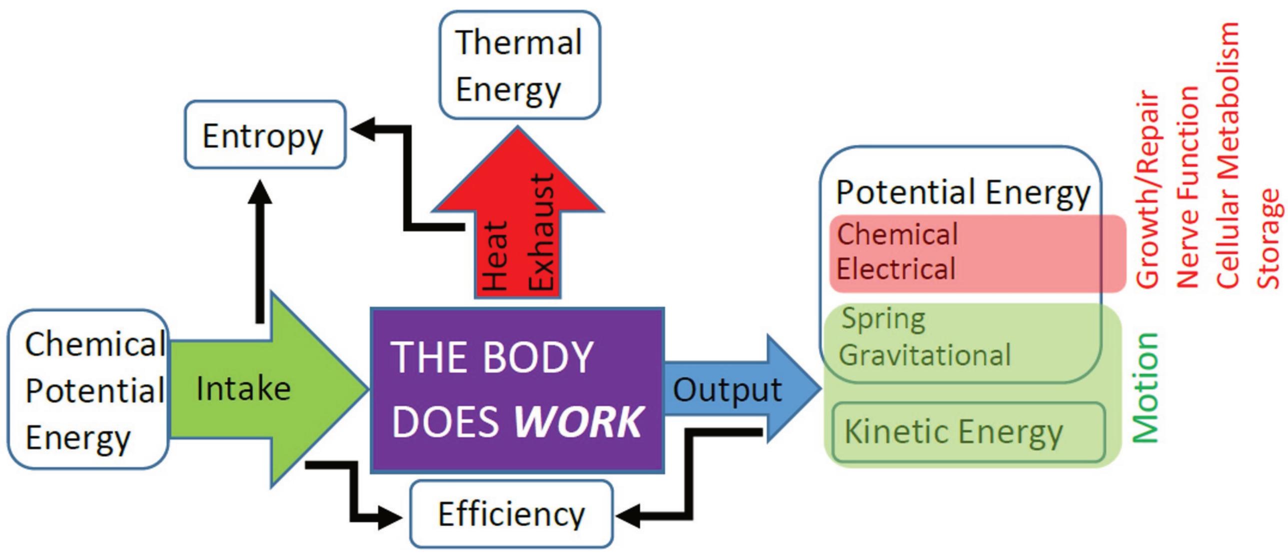
Basal Metabolic Rates (BMR)

organ	power consumed at rest (w)	oxygen consumption (ml/min)	percent of bmr
Liver & spleen	23	67	27

1. Significant content in this chapter was adapted from: OpenStax, College Physics. OpenStax CNX. Aug 30, 2019 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@17.22

organ	power consumed at rest (w)	oxygen consumption (ml/min)	percent of bmr
Brain	16	47	19
Skeletal muscle	15	45	18
Kidney	9	26	10
Heart	6	17	7
Other	16	48	19
Totals	85 W	250 mL/min	100%

The largest fraction of energy goes to the liver and spleen, with the brain coming next. About 75% of the calories burned in a day go into these basic functions. A full 25% of all basal metabolic energy consumed by the body is used to maintain electrical potentials in all living cells. (Nerve cells use this electrical potential in nerve impulses.) This bioelectrical energy ultimately becomes mostly thermal energy, but some is utilized to power chemical processes such as in the kidneys and liver, and in fat production. The BMR is a function of age, gender, total body weight, and amount of muscle mass (which burns more calories than body fat). Athletes have a greater BMR due to this last factor. Of course, during vigorous exercise, the energy consumption of the skeletal muscles and heart increase markedly. The following diagram summarizes the basic energetic functioning in the human body.



The most basic functions of the human body mapped to the main concepts covered in this textbook.(Chemical potential energy is actually a form of electric potential energy, but we will not specifically discuss electric potential energy in this textbook so we have separated the two.)

THE FIRST LAW OF THERMODYNAMICS

HEAT

The body is capable of storing chemical potential energy and thermal energy internally. Remembering that thermal energy is just the kinetic energy of atoms and molecules, we recognize that these two types of energy are stored microscopically and internal to the body. Therefore, we often lump these two types of microscopic energy into the internal energy (U). When on object is warmer then its surroundings then thermal energy will be transferred from object to surroundings, but if the object is cooler than its surroundings then thermal energy will transferred into the object from its surroundings. The amount of thermal energy exchanged due to temperature differences is often called heat (Q). When heat is transferred out of the body to the environment, we say call this exhaust heat, as indicated in the previous figure. We will learn more about how temperature and heat transfer are related in the next unit.

ENERGY CONSERVATION

The Principle of Conservation of Energy states that energy cannot be created or destroyed. Therefore, if the body does useful work to transfer mechanical energy to its surroundings (W_{by}), or transfer thermal energy to the environment as heat, then that energy must have come out of the body's internal energy. We observe this throughout nature as the First Law of Thermodynamics:

(1) $$\Delta U = Q - W_{by}$$

HEAT ENGINES

Your body uses chemical potential energy stored internally to do work, and that process also generates thermal energy, which you release as exhaust heat. The internal combustion engines that power most cars operate in similar fashion by converting chemical potential energy in fuel to thermal energy via combustion, then converting some of the thermal energy into useful work and dumping some into exhaust heat. Your body is capable of releasing the chemical potential energy in your food without combustion, which is good, because you are not capable of using thermal energy your from yourinternal energy to do work. Machines that can use thermal energy to do work, such as a combustion engine, are known as heat engines. Heat engines are still governed by the First Law of Thermodynamics, so any exhaust heat must have been thermal energy that was not used to do work. The thermal energy input that can be used to do work rather than wasted as exhaust heat determines the efficiency of the heat engine.

BODY EFFICIENCY

The efficiency of the human body in converting chemical potential energy into useful work is known as the mechanical efficiency of the body. We often calculate the body's mechanical efficiency, as a percentage:

(2) $$e_{body} = \frac{W_{by}}{Chemical\,Potential\,Energy\,Used} \times 100\,\%$$

The mechanical efficiency of the body is limited because energy used for metabolic processes cannot be used to do useful work. Additional thermal energy generated during the chemical reactions that power muscle contractions along with friction in joints and other tissues reduces the efficiency of humans even further.[2].

2. "The maximum work and mechanical efficiency of human muscles, and their most economical speed" by A. V. Hill,National Library of Medicine, U.S. National institutes of Health

Reinforcement Exercises

"Alas, our bodies are not 100 % efficient at converting food energy into mechanical output. But at about 25 % efficiency, we're surprisingly good considering that most cars are around 20 %, and that an Iowa cornfield is only about 1.5 % efficient at converting incoming sunlight into chemical [potential energy] storage." [3]For an excellent discussion of human mechanical efficiency and comparisons with other machines and fuel sources, see MPG of a Human by Tom Murphy, the source of the previous quote.

Everyday Example: Energy to Climb Stairs

Assuming a 20% mechanical efficiency in climbing stairs, how much does your internal energy decrease when a 65 **kg** person climbs a 15 **m** high flight of stairs? How much thermal energy does the person transfer to the environment as exhaust heat?

First, lets calculate the change in gravitational potential energy:

$$\Delta PE_g = mg\Delta h = (65\,\mathbf{kg})(9.8\,\mathbf{m/s/s})(15\,\mathbf{m}) = 9,555\,\mathbf{J}$$

The person did work in converting chemical potential energy in their body to mechanical energy, specifically gravitational potential energy. However, they are only 20% efficient, which means that only 1/5 of the chemical potential energy they use goes into doing useful work. Therefore the change in chemical potential energy must have been 5x greater than the mechanical work output

$$Chemical\;Potential\;Energy\,Used = (5 \times 9,555\,\mathbf{J}) = 47,775\,\mathbf{J}$$

The chemical potential energy used came out of the person's internal energy so:

$$\Delta U = -47,775\,\mathbf{J}$$

We can use the First Law of Thermodynamics to find the thermal energy exhausted by the person:

(3) $$\Delta U = Q - W_{by}$$

Rearranging for Q:

$$Q = \Delta U + W_{by} = -47,775\,\mathbf{J} + 9,555\,\mathbf{J} = -38,220\,\mathbf{J}$$

We find that the heat is negative, which makes sense because the person exhausts thermal energy out of the body and into to the environment while climbing the stairs.

An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=1067

3. "MPG of a Human" by Tom Murphy, Do The Math, UCSD Physics Department

Alternatively, we could have known right off that the exhaust heat must be 4/5 of the total loss of internal energy, because only 1/5 went into doing useful work. So the exhaust heat should be:

$Q = \Delta U \times (4/5) = -47,775\,\mathbf{J} \times 4/5 = -38,220\,\mathbf{J}$

FOOD CALORIES

For historical reasons we often measure thermal energy and heat in units of calories (**cal**) instead of Joules. There are 4.184 Joules per calorie. We measure chemical potential energy stored in food with units of 1000 calories, or kilocalories (**kcal**) and we sometimes write kilocalories as Calories (**Cal**) with with capital ***C*** instead of a lowercase ***c***. For example, a bagel with 350 **Cal** has 350 **kcal**, or 350,000 **cal**. Converting to Joules, that would be $350,000\,\mathbf{cal} times (4.184\,\mathbf{J}/boldcal) = 1,464,400\,\mathbf{J}$ in the bagel.

Everyday Examples

What fraction of a bagel would you need to eat in order to make up for the 47,775 **J** loss of internal energy (as chemical potential energy) that we calculated in the previous everyday example about climbing stairs?

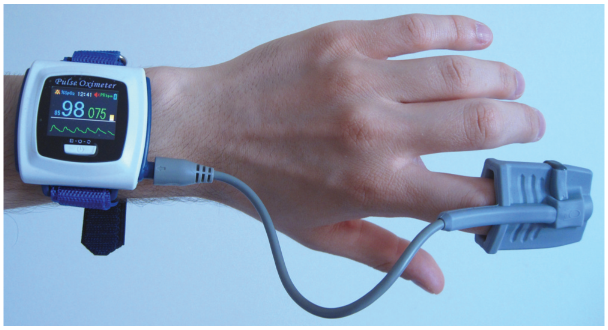
There are 1,464,400 **J**/bagel

Therefore we need to eat:

$$\frac{47,775\,\mathbf{J}}{1,464,400\,\mathbf{J}/bagel} = 0.03\,Bagels\,or\,3\,\%\,of\,a\,bagel$$

Reinforcement Exercises

CONSERVATION OF MASS AND OF ENERGY



A pulse oxymeter is an apparatus that measures the amount of oxygen in blood. Oxymeters can be used to determine a person's metabolic rate, which is the rate at which food energy is converted to another form. Such measurements can indicate the level of athletic conditioning as well as certain medical problems. (credit: UusiAjaja, Wikimedia Commons)

The digestive process is basically one of oxidizing food, so energy consumption is directly proportional to oxygen consumption. Therefore, we can determine the the actual energy consumed during different activities by measuring oxygen use. The following table shows the oxygen and corresponding energy consumption rates for various activities.

Energy and Oxygen Consumption Rates for an average 76 kg male

activity	energy consumption in watts	oxygen consumption in liters o_2/min
Sleeping	83	0.24
Sitting at rest	120	0.34
Standing relaxed	125	0.36
Sitting in class	210	0.60
Walking (5 km/h)	280	0.80
Cycling (13–18 km/h)	400	1.14
Shivering	425	1.21
Playing tennis	440	1.26

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activity	energy consumption in watts	oxygen consumption in liters O_2/min
Swimming breaststroke	475	1.36
Ice skating (14.5 km/h)	545	1.56
Climbing stairs (116/min)	685	1.96
Cycling (21 km/h)	700	2.00
Running cross-country	740	2.12
Playing basketball	800	2.28
Cycling, professional racer	1855	5.30
Sprinting	2415	6.90

Everyday Examples: Climbing Stairs Again

In the previous examples we assumed stated that our mechanical efficiency when climbing stairs was 20%. Let's use the data in the above table to verify that assumption. The data in the table is for a 76 **kg** person climbing 116 stairs per minute. Let's calculate the rate at which that person did mechanical work while climbing stairs and compare that rate at which they used up internal energy (originally from food).

The minimum standard step height in the US is 6.0 inches[4] (0.15 **m**) then the gravitational potential energy of a 76 **kg** person will increase by 130 **J** with each step, as calculated below:

$$\Delta PE = mg\Delta h = (76\,\mathbf{kg})(9.8\,\mathbf{m/s/s})(0.15\,\mathbf{m}) = 112\,\mathbf{J}$$

When climbing 116 stairs per minute the rate of energy use, or power, will then be:

$$P = (112\,\mathbf{J})\left(116\,\frac{stairs}{\mathbf{min}}\right)\left(\frac{1\,\mathbf{min}}{60\,\mathbf{sec}}\right) = 216\,\mathbf{W}$$

According to our data table the body uses 685 **W** to climb stairs at this rate. Let's calculate the efficiency:

$$e = \frac{216\,\mathbf{W}}{685\,\mathbf{W}} = 0.32$$

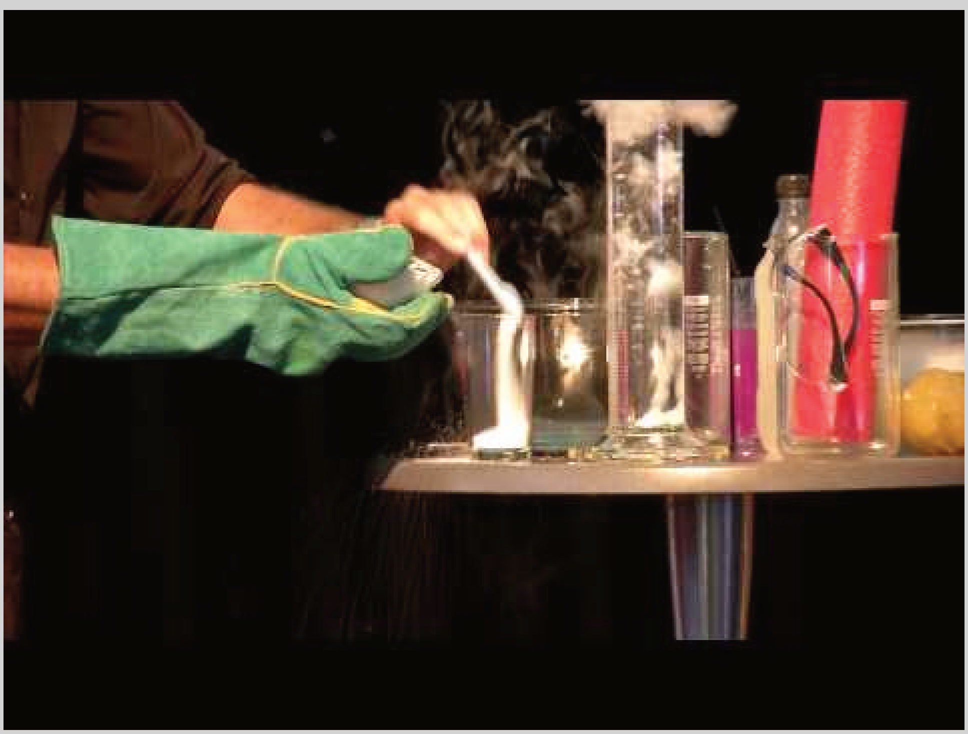
As a percentage, this person is 32% mechanically efficient when climbing stairs. We may have underestimated in the previous examples when we assumed a 20% efficiency for stair climbing.

Reinforcement Exercises

An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=1067

4. "1917.120 - Fixed stairways." by Occupational Safety and Health Administration, United States Department of Labor

We often talk about "burning" calories in order to lose weight, but what does that really mean scientifically?. First, we really we mean lose mass because that is the measure of how much stuff is in our bodies and weight depends on where you are (it's different on the moon). Second, our bodies can't just interchange mass and energy — they aren't the same physical quantity and don't even have the same units. So how do we actually lose mass by exercising? We don't actually shed the atoms and molecules that make up body tissues like fat by "burning" them. Instead, we break down the fat molecules into smaller molecules and then break bonds within those molecules to release chemical potential energy, which we eventually convert to work and exhaust heat. The atoms and smaller molecules that resulting from breaking the bonds combine to form carbon dioxide and water vapor (CO_2 and H_2O) and we breath them out. We also excrete a bit as H_2O in sweat and urine. The process is similar to burning wood in campfire — in the end you have much less mass of ash than you did original wood. Where did the rest of the mass go? Into the air as CO_2 and H_2O. The same is true for the fuel burned by your car. For more on this concept see the first video below. The really amazing fact is that your body completes this chemical process without the excessive temperatures associated with burning wood or fuel, which would damage your tissues. The body's trick is to use enzymes, which are highly specialized molecules that act as catalysts to improve the speed and efficiency of chemical reactions, as described and animated in the beginning of the second video below.



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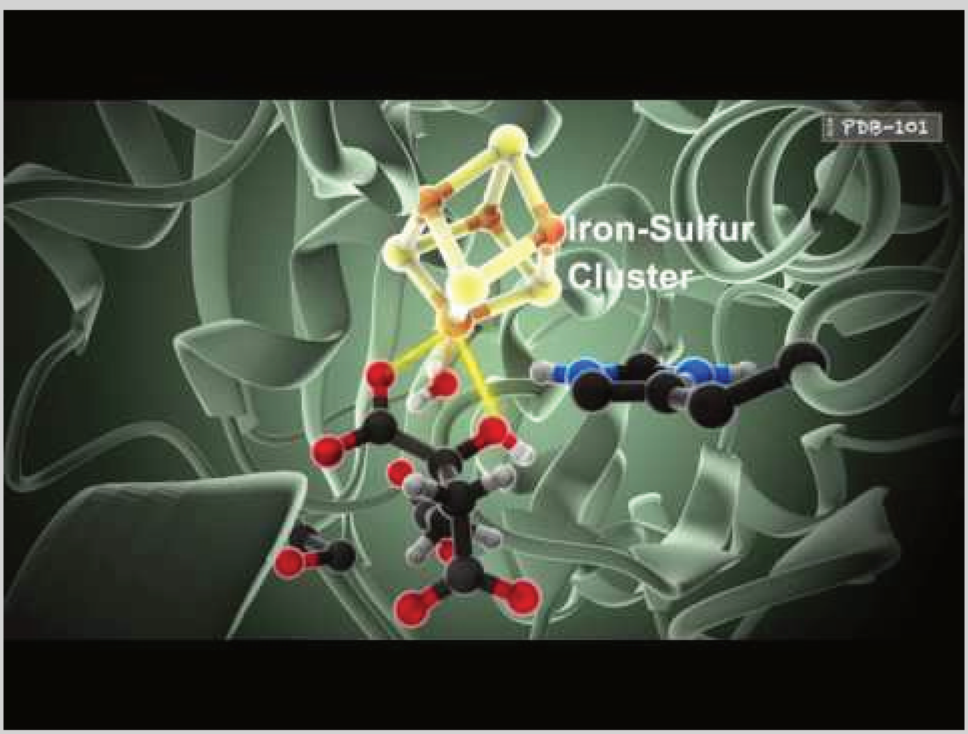
GENERAL EFFICIENCY

Similar to the body efficiency, the efficiency of any energetic process can be described as the amount of energy converted from the input form to the desired form divided by the original input amount. The following chart outlines the efficiencies of various systems at converting energy various forms. The chart does not account for the cost, hazard risk, or environmental impact associated with the required fuel, construction, maintenance, and by-products of each system.

The Efficiency of the Human Body Compared to Other Systems

System	Input Energy Form	Desired Output Form	Max Efficiency
Human Body	Chemical Potential	Mechanical	25 %
Automobile Engine	Chemical Potential	Mechanical	25 %
Coal/Oil/Gas Fired Stream Turbine Power Plants	Chemical Potential	Electrical	47%
Combined Cycle Gas Power Plants	Chemical Potential	Electrical	58 %
Biomass/Biogas	Kinetic	Electrical	40%
Nuclear	Kinetic	Electrical	36%
Solar-Photovoltaic Power Plant	Sunlight (Electromagnetic)	Electrical	15%
Solar-Thermal Power Plant	Sunlight (Electromagnetic)	Electrical	23%
Hydroelectric and Tidal Power Plants	Gravitational Potential	Electrical	90%+



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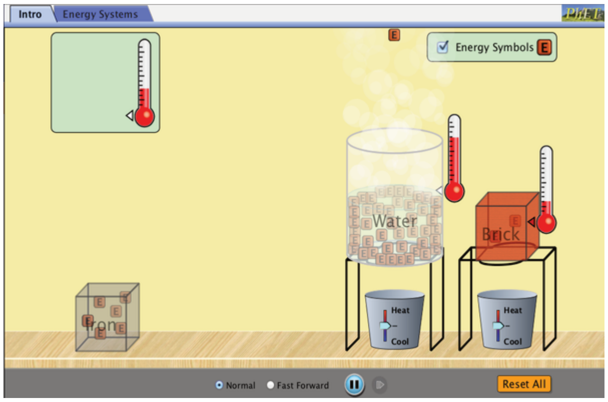
Check out the energy systems tab in this simulation to visualize different energy conversion systems



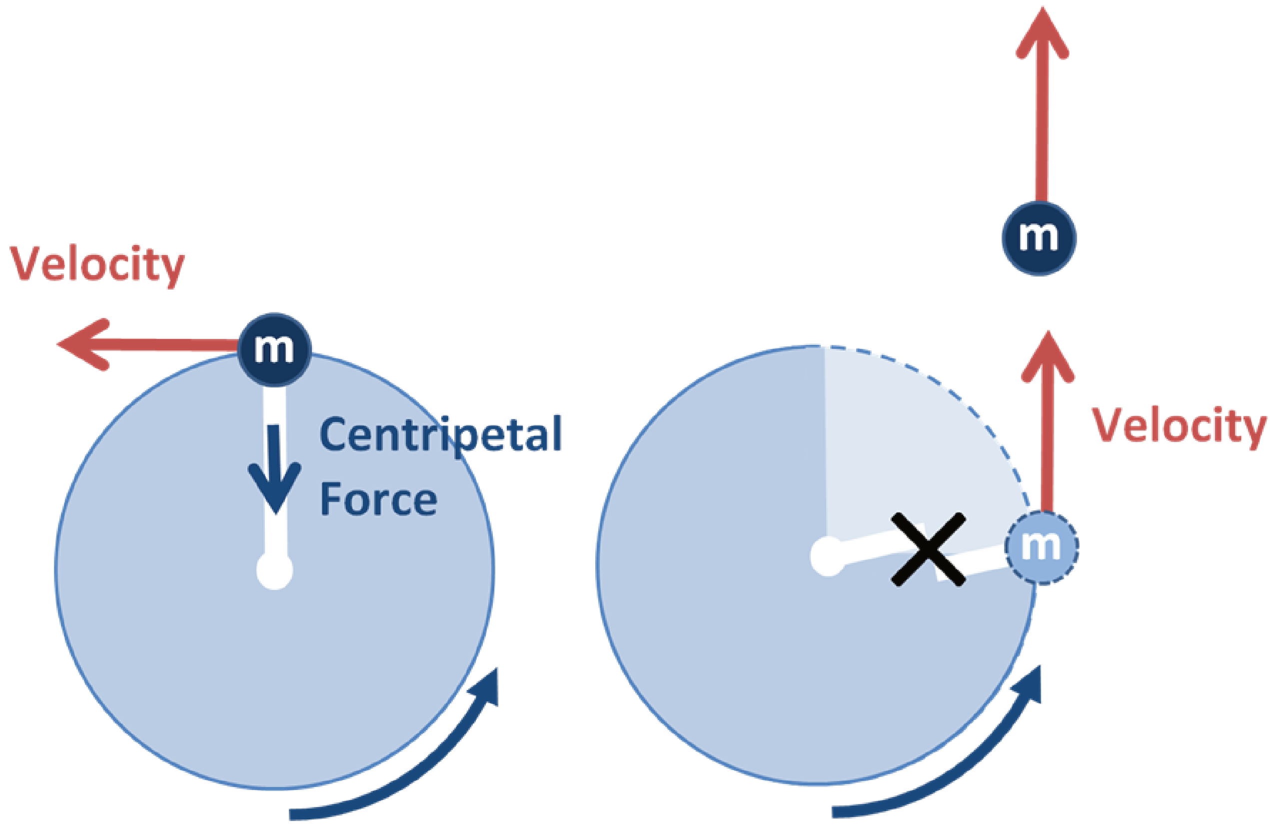
5. "Managing Water in the West: Hydroelectric Power" by Bureau of Reclimation, U.S. Department of the Interior
6. "Efficiency in Electricity Generation" by EURELECTRIC "Preservation of Resources" Working Group's "Upstream" Sub-Group in collaboration with VGB, Union of the Electricity Industry
7. "Efficiency of Energy Conversion Devices" by John E. Dutton e-Education Institute, Penn State College of Earth and Mineral Sciences

CHAPTER 84.

WEIGHTLESSNESS*

UNIFORM CIRCULAR MOTION

We have seen that if the net force is found to be perpendicular to an object's motion then it can't do any work on the object. Therefore, the net force will only change the object's direction of motion, change it's kinetic energy) and the object must maintain a constant speed. The object will undergo uniform circular motion, in which case we sometimes refer to the net force that points toward the center of the circular motion as the centripetal force, but this is just a naming convention. *The centripetal force is not a new kind of force, rather the centripetal force is provided by one of the forces we already know about, or a combination of them.* For example, the centripetal force that keeps a satellite in orbit is just gravity and for a ball swinging on a string tension in the string provides the centripetal force.



Left: A ball on a string undergoing circular motion with uniform (constant) speed. Right: The ball's trajectory after the string breaks . Image Credit: Breaking String by Brews ohare via Wikimedia Common

[1]

For both the ball and the satellite the net force points at 90° to the object's motion so it can do no work, thus it cannot change the kinetic energy of the object, which means it cannot change the speed of the object. How do we mesh this with Newton's Second Law, which says that objects with a net force must experience acceleration? We just have to remember that acceleration is change velocity per time and velocity includes speed and direction. Therfore, the constantly changing direction of uniform circular motion constitutes a constantly changing velocity, and thus a constant acceleration, so all is good. Due to Newton's Second Law, we know that the acceleration points toward the center of the circular motion because that is where the net force points. As a result, that acceleration is called the centripetal acceleration. If the net force drops to zero (string breaks) the acceleration must become zero and the ball will continue off at the same speed in whatever direction it was going when the net force became zero (diagram on right above).

CENTRIPETAL FORCE AND ACCELERATION

The size of the acceleration experienced by an object undergoing uniform circular motion with radius r at speed v is:

1. Breaking String by Brews ohare [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0) or GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons

(1) $$a_c = \frac{v^2}{r}$$

Combined with Newton's Second Law we can find the size of the centripetal force, which again is just the net force during uniform circular motion:

(2) $$F_{net} = ma = m\frac{v^2}{r}$$

Everyday Example: Rounding a Curve

What is the maximum speed that a car can have while rounding a curve with radius of 75 **m** without skidding? Assume the friction coefficient between tire rubber and the asphalt road is 0.7

First, we recognize that as the car rounds the curve at constant speed the net force must point toward the center of the curve and have the value:

$$F_{net} = m\frac{v^2}{r}$$

Next we recognize that the only force available to act on the car in the horizontal direction (toward the center of the curve) is friction, so the net force in the horizontal direction must be just the frictional force:

$$F_f = m\frac{v^2}{r}$$

We want to know the maximum speed to take the curve without slipping, so we need to use the maximum static frictional force that can be applied before slipping:

$$\mu_s F_N = m\frac{v^2}{r}$$

Notice that we have used static friction even though the car is moving because we are solving the case when the tires are still rolling and not yet sliding. Kinetic friction would be used if the tires were sliding.

For a typical car on flat ground the normal force will be equal to the weight of the car:

$$\mu_s mg = m\frac{v^2}{r}$$

Then we cancel the mass from both sides of the equation and solve for speed:

$$v = \mu_s gr$$

Inserting our values for friction coefficient, *g*, and radius:

$$v = sqrt0.7(9.8\,\mathbf{m/s})(75\,\mathbf{m}) = 22\,\mathbf{m/s} = 49\,\mathbf{MPH}$$

The inverted airfoils (wings) on a shape of a formula one race car create a downward aerodynamic force, increasing normal force from the road and thus friction as well. Image Credit: Italian V12 by Rob Oo via Wikimedia Commons

[2]

WEIGHTLESSNESS

When you stand on a scale and you are not in equilibrium, then the normal force may not be equal to your weight and the weight measurement provided by the scale will be incorrect. For example, if you stand on a scale in an elevator as it begins to move upward, the scale will read a weight that is too large. As the elevator starts up, your motion changes from still to moving upward, so you must have an upward acceleration and you must not be in equilibrium. The normal force from the scale must be larger than your weight, so the scale will read a value larger than your weight.

In similar fashion, if you stand on a scale in an elevator as it begins to move downward the scale will read a weight that is too small. As the elevator starts down, your motion changes from still to moving downward, so you must not be in equilibrium, rather you have a downward acceleration. The normal force from the scale must be less than your weight.

Taking the elevator example to the extreme, if you try to stand on a scale while you are in free fall, the scale will be falling with the same acceleration as you. The scale will not be providing a normal force to hold you up, so it will read your weight as zero. We might say you are *weightless*. However, your weight is certainly not zero because weight is just another name for the force of gravity, which is definitely acting on you while you free fall. Maybe *normal-force-less* would be a more accurate, but also less convenient term than weightless.

We often refer to astronauts in orbit as weightless, however we know the force of gravity must be acting on them in order to cause the centripetal acceleration required for them to move in a circular orbit. Therefore, they are not actually weightless. The astronauts feel weightless because they are in free fall along with everything else around them. A scale in the shuttle would not read their weight because it would not need to supply a normal force to cancel their weight because both the scale and the astronaut are in free fall toward Earth. The only reason they don't actually fall to the ground is that they are also moving so fast perpendicular to their downward acceleration that by the time they would have hit the ground, they have moved sufficiently far to the side that they end up falling *around* the Earth instead of *into* it.

Everyday Example: Orbital Velocity

How fast does an object need to be moving in order to free fall around the Earth (remain in orbit)? We can answer that question by setting the centripetal force equal to the gravitational force, given by Newton's Universal Law of Gravitation (F_g = mg is only valid for object near Earth's surface, remember):

$$F_g = \frac{Gm_1m_2}{r^2}$$

Recognizing that gravity is the centripetal force in this case, and that m_1 is the Earth's mass and m_2 is the orbiting object's mass:

$$\frac{Gm_1m_2}{r^2} = m_2\frac{v^2}{r}$$

2. Rob Oo from NL [CC BY 2.0 (https://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons

$$\frac{Gm_1m_2}{r^2} = m_2\frac{v^2}{r}$$

Cancelling m_2 and one factor of r from both sides and solving for speed:

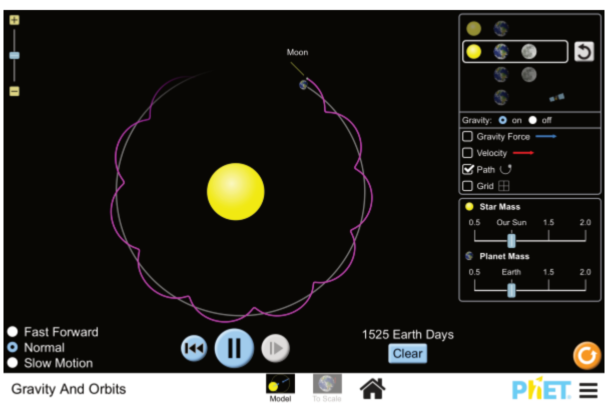
$$v = \sqrt{\frac{Gm_1}{r}}$$

We see that the necessary orbit speed depends on the radius of the orbit. Let's say we want a low-Earth orbit at an altitude of 2000 **km**, or $2000 \times 10^3\,\mathbf{m}$. The radius of the orbit is that altitude plus the Earth's radius of $6378\,\mathbf{km}$ to get $r = 8378\,\mathbf{km}$ or $r = 8378 \times 10^3\,\mathbf{m}$. Inserting that total radius and the gravitational constant, $G = 6.67408 \times 10^{-11}\,\mathbf{m^3kg^{-1}s^{-2}}$, and the Earth's mass: $m_1 = 5.972 \times 10^{24}\,\mathbf{kg}$:

$$v = \sqrt{\frac{(6.67408 \times 10^{-11}\,\mathbf{m^3kg^{-1}s^{-2}})(5.972 \times 10^{24}\,\mathbf{kg})}{(8378 \times 10^3\,\mathbf{m})}} \approx 7000\,\mathbf{m/s} \approx 15,000\,\mathbf{MPH}$$

That's fast.

Use this simulation to play with the velocities of these planets in order to create stable orbits around the sun.



CHAPTER 85.

COMPARING WORK-ENERGY AND ENERGY CONSERVATION*

In the previous chapters we analyzed a person's jump using the work-energy principle rather than the Law of Conservation of Energy. Examining that correspondence between these concepts will allow us to learn a few important concepts. Let's refresh ourselves with that example:

Everyday Examples: Jumping

During a jump a person's legs might apply a force of 1200 **N** upward on their center of mass while the center of mass moves 0.3 **m** upward. Let's figure out what their launch speed and hang time will be if the person has a weight of 825 **N**.

First we calculate the work done by their legs.

$$W_L = F_L d cos\theta = (1200\,\mathbf{N})(0.3\,\mathbf{m})cos(0^\circ) = 360\,\mathbf{J}$$

Gravity was acting on them during the launch phase as well, so we need to calculate the work done by gravity:

$$W_g = F_g d cos\theta = (825\,\mathbf{N})(0.3\,\mathbf{m})cos(180^\circ) = -247.5\,\mathbf{J}$$

The net work is then:

$$W_{net} = -247.5\,\mathbf{J} + 360\,\mathbf{J} = 112.5\,\mathbf{J}$$

The work-energy principle tells us to set the change in kinetic energy equal to the net work. We will keep in mind that they started at rest, so the initial kinetic energy was zero.

$$112.5\,\mathbf{J} = \frac{1}{2}mv_f^2 - 0$$

We can see that we need the person's mass. We just divide their weight by *g*= 9.8 **m/s/s** to find it:

$$m = \frac{825\,\mathbf{N}}{9.8\,\mathbf{m/s}} = 84.2\,\mathbf{kg}$$

We isolate the final speed at the end of the launch phase (as the person leaves the ground) and insert the mass.

$$\frac{2(112.5\,\mathbf{J})}{84.2\,\mathbf{kg}} = v_f^2$$

Then we take the square root the result to find the speed:

$$v_f = \sqrt{\frac{2(112.5\,\mathbf{J})}{84.2\,\mathbf{kg}}} = 1.6\,\mathbf{m/s}$$

In the first part of the jumping example we calculated the net work on the object and used the work-energy principle to find the change in kinetic energy. In equation form it looks like this:

$W_L + W_g = \Delta KE$

Moving the work done by gravity to the other side:

$W_L = \Delta KE - W_g$

The Law of Conservation of Energy looks like this:

$W_{on} = \Delta KE + \Delta PE + \Delta TE$

Remembering that we ignored friction and air resistance, and that nothing was permanently deformed, $\Delta TE = 0$.

$W_{on} = \Delta KE + \Delta PE + 0$

Gravity did negative work because it points down and motion was upward, but the effect of that work was to increase potential energy by transferring some of the person's kinetic energy into their owngravitational potential energy. Therefore change in gravitational potential energy should be the negative of the work done by gravity. This work was internal to the Earth-person system, so the only work being done on the person's center of gravity from the outside was work done by the legs. Making these replacements we have:

$W_L = \Delta KE - W_g$

Which is exactly the work-energy principle we started with. We can either use the work-energy principle on a given object and include work done by resistance to compression and gravity in the net work, and say all of that work contributes to changing kinetic energy, or instead use the Law of Conservation of Energy and instead say that work done by elastic forces and gravity contributes to elastic potential energy and gravitational potential energy instead of kinetic energy. Either way is equivalent, as we have just seen.

CHAPTER 86.

UNIT 9 REVIEW

Key Terms and Concepts

Work

Work-Energy Principle

Gravitational Potential Energy

Law of Conservation of Energy

Chemical Potential Energy

Power

Internal Energy

First Law of Thermodynamics

Efficiency

Calories

Learner Outcomes

1. Define, recognize, and differentiate work, kinetic energy, and potential energy, including elastic, gravitational, and chemical.[2]
2. Apply the Law of Conservation of Energy and The First Law of Thermodynamics to the analysis of physical processes.[3]
3. Determine the efficiency of physical processes and machines.[3]
4. Evaluate the power output of machines.[3]

CHAPTER 87.

UNIT 9 PRACTICE AND ASSESSMENT

Outcome 1

1) A rubber ball is lifted to a height of 3.0 **m** at constant speed and then dropped. The ball bounces off the floor below and returns to a height of 2.2 **m**.

a) Does the ball have the same mechanical energy after the bounce as before? If not, where did that mechanical energy go?

2) Fill in the blanks in the following statements about the ball in question 1) using the terms listed. Don't forget that the body is not 100% efficient.

- chemical potential
- gravitational potential
- elastic potential
- kinetic
- thermal
- positive
- negative
- zero

a) While lifting the ball up, ____________________energy is being exchanged for _________________ energy. The exchange occurs as you do __________work and gravity does __________ work. The ball moves at constant speed because the net work is ________.

b) While falling, gravity is the only force doing work and that work is _____________, therefore the net work is __________ and __________energy is increasing. Overall, ____________________energy is being exchanged for _________________ energy.

c) While in contact with the floor and compressing, the normal force from the floor is doing _________ work, gravity is doing_____________ work. The ball is slowing down so net work must be ___________. Therefore the normal force must be larger than the weight of the ball. Overall, __________________energy and a bit of gravitational potential energy are being exchanged for

_______________ energy and ______________energy. (Remembering that the ball does not reach the same height after bouncing).

d) While in contact with the floor and decompressing, the normal force from the floor is doing _________ work, gravity is doing_____________ work. The ball is speeding up so net work must be ___________. Therefore the normal force must be larger than the weight of the ball. Overall, __________________energy is being exchanged for _______________ energy ___________energy and a bit of gravitational potential energy.

e) While rising, gravity is the only force doing work and that work is _____________, therefore the net work is __________ and __________energy is decreasing. Overall, ____________________energy is being exchanged for _________________ energy.

f) Where did the energy come from to do the original work of lifting the ball to increase gravitational potential energy?

Outcome 2

3) In the absence of gravity or friction, a spaceship engine supplies 55,000 **N** of thrust force to a 1500 **kg** ship.

a) Use the work-energy principle to determine what distance the rocket will cover before it reaches a speed of 1200 **m/s** , starting from rest.

b) Use the impulse-momentum theorem (discussed in the previous unit) to determine how long it will take the rocket to get up to 1200 **m/s** speed. (This is also how long it took to cover that distance you found above).

4) A car is moving at 55 **mph** (26 **m/s**)on flat ground when a hazard is spotted 85 **m** (278 **ft**) ahead. (Such as deer, tree-limb, or broke-down car in the road).

a) What distance does the car travel before the brakes are even applied if the driver takes typical 1.5 **s** braking reaction time? [1]

b) Draw a free body diagram of this car, while brakes are applied.

c) What is the normal force on the car?

d) If the car slams on the brakes what is the frictional force? Assume that the car has anti-lock bakes that prevent sliding and the static friction coefficient between tire rubber and dry asphalt is 0.7.

e) Use the work-energy principle to determine the stopping distance.

f) What is the total stopping distance including distance covered during the reaction time and braking? Does an accident occur?

Outcome 3

5) A person uses a pulley system with mechanical advantage of three to lift a 65 **kg** load a distance of 0.5 **m.**

a) What force should the person need to apply?

1. "Why your reaction time matters at speed" by National Highway Traffic Safety Administration, U.S. Department of Transportation

b) What distance do they need to pull the rope? [Hint: Assuming friction in the pulleys is small enough to ignore, the work input to the pulley system and work output need to be the same].

b) How much potential energy is gained by the load?

c) If the person actually had to pull with 701 **N** due to friction in the system, how much work did they actually do?

d) What is the mechanical efficiency of this system?

e) Remembering that the body is only 20% mechanically efficient, how much chemical potential energy did the person expend?

6) Recently Colin Haley set a speed record for ascending the classically difficult Cassin Ridge on Denali, the highest mountain in North America, located in Central Alaska. Haley started from the glacier at the foot of the mountain and climbed 8000 **ft** to reach the 20,310 **ft** summit in 487 minutes. [2]

a) If Colin plus his clothes, gear, and light pack had a combined weight of 72 **kg**, how much gravitational potential energy did Colin gain (in units of Joules)?

b) If Colin is 15% mechanically efficient climbing ice and slogging through snow, how many Joules of chemical potential energy did he actually expend?

c) How many Joules of chemical potential energy were converted to exhaust heat?

Outcome 4

d) What was Colin's average mechanical power output in Watts?

e) What was Colin's average thermal power output in Watts?

f) What was Colin's total average power output in Watts?

g) How many 260 Calorie candy bars would Colin need to eat during his climb in order maintain a constant internal energy? [Hint: Remember, Calories are not the same as calories]

7) A typical microwave oven requires 1,100 **W** of electric power. The microwave needs 2.0 minutes to bring 0.25 **kg** of room-temperature water to a boil.

a) How much electrical potential energy does the microwave use in that time?

b) The thermal energy required to raise the temperature of 0.25 **kg** water from room temp to boiling is 84,000 **J** (more on this in the next unit). What is the efficiency of the microwave in converting electrical potential energy to thermal energy in water?

2. "Colin Haley Sets New Speed Record on Denali's Cassin Ridge" by Michael Levy, Rock and Ice Magazine

PART X.

UNIT 10: BODY HEAT AND THE FIGHT FOR LIFE

Learner Objectives

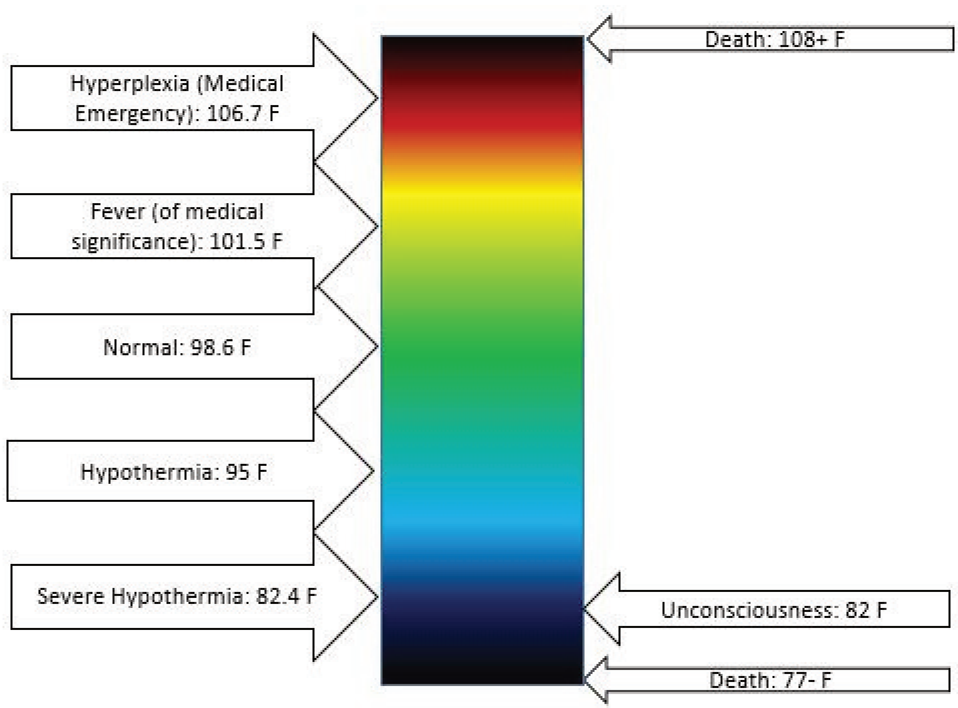
1. Compare, contrast, and convert between absolute and relative temperature scales.[1]
2. Evaluate the effectiveness of various types of insulation against different mechanisms of heat transfer.[3]
3. Apply the concepts of temperature, thermal expansion, specific heat, heat capacity, and latent heat, to analyze how physical objects respond to heat transfer.[3]
4. Apply the Second Law of Thermodynamics to predict the outcome of physical scenarios.[2]

CHAPTER 88.

HOMEOSTASIS, HYPOTHERMIA, AND HEATSTROKE

HOMEOSTATIS

In the previous unit we learned that the body is at best only 25 % efficient at converting chemical potential energy to useful work. The other 75% of the chemical potential energy becomes thermal energy, which the body exploits to manage body temperature as a part of homeostasis, or the body's act of maintaining a relatively constant internal environment. Thermal injuries occur when body temperature becomes to high or too low, but our body has strategies for preventing that from occuring.



False-color scale indicating medically-relevant body temperature thresholds. Image Credit:Human Body Temperature Scale by Foxtrot620 via Wikimedia Commons

1

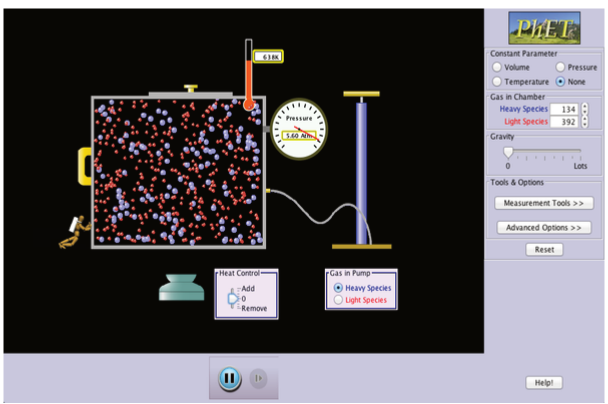
1. Human Body Temperature Scale by Foxtrot620 [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], from Wikimedia Commons

In order to analyze our body's response to different environmental temperatures we need to first define temperature and clear up the definitions for some other thermodynamic quantities:

1. Thermal energy(*TE*): Kinetic energy stored in the microscopic motion of atoms and molecules. The SI unit for thermal energy is Joules (**J**), though it is sometimes measured in calories or British Thermal Units (**BTU**)
2. Temperature (*T*): A measure of the *average* thermal energy per atom or molecule. The SI unit for Temperature is Kelvin (**K**), though it is often measured in Celsius (°**C**) or degrees Fahrenheit (°**F**).
3. Heat(*Q*):The amount of thermal energy transferred between an object and its environment due to a difference in the object and environment temperatures. The units for heat are the same as for thermal energy.
4. Thermal Equilibrium: A state where the rate of heat transfer is zero because object and environmental temperatures are the same.

Reinforcement Exercise

The following simulation allows you to visualize how temperature and atomic motion are related.



THERMAL INJURIES

Now that we have solid definitions for thermal energy, heat, temperature, and thermal equilibrium, we can follow the progression of thermal injuries:

1. As a measure of the average motion of atoms and molecules, temperature influences the rate of chemical reactions and the ability of molecules, such as proteins, to remain in a particular shape.

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https://openoregon.pressbooks.pub/bodyphysics/?p=1064

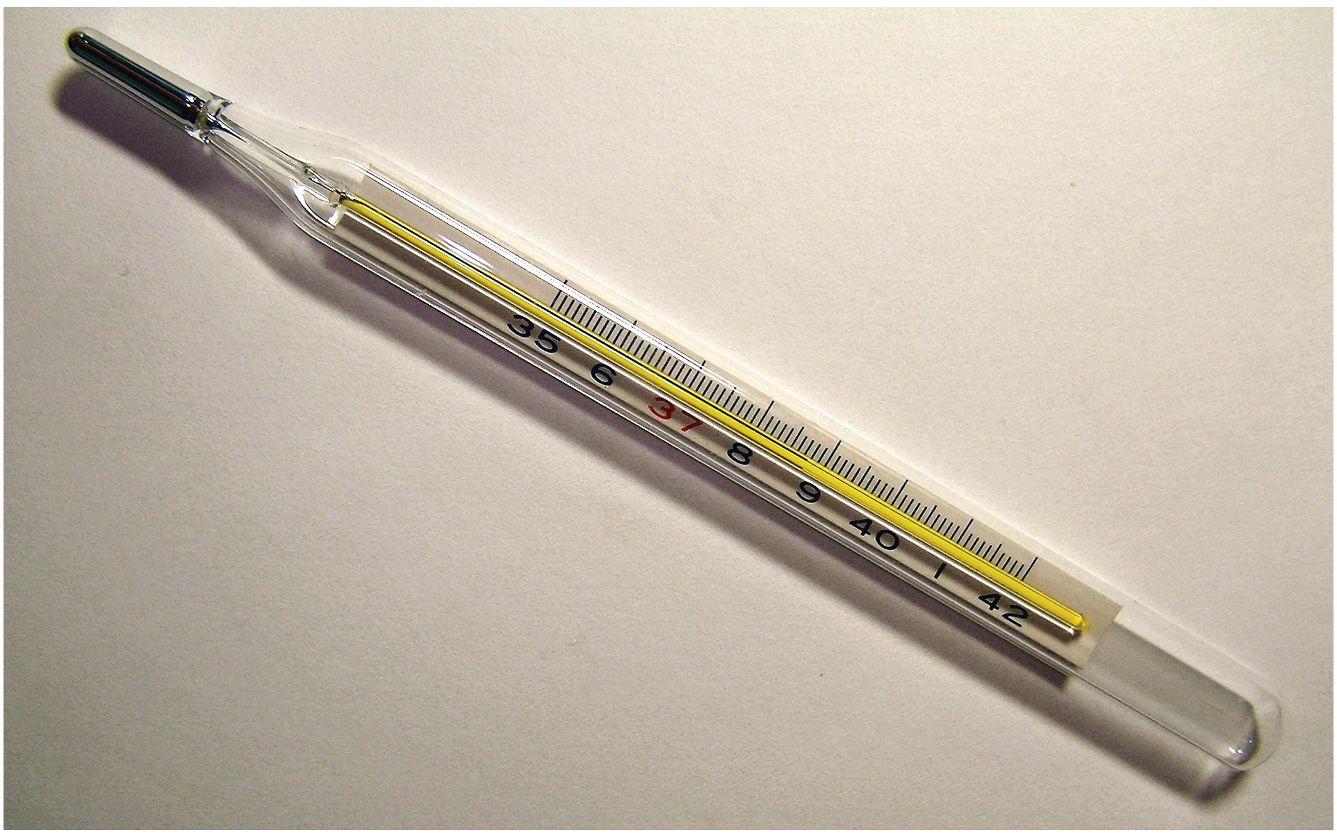
2. Due to the above, the body must maintain a relatively narrow range of temperature in order to function properly.
3. The body is inefficient and thus converts chemical potential energy to primarily thermal energy as part of basic metabolism and when doing useful work.
4. If heat transfer is limited, then thermal energy will build up in the body and temperature will increase, possibly resulting in hyperthermia and heat-related injuries such as heat stroke. We will learn to prevent hyperthermia by understanding how and when heat transfer to the environment is limited in the following chapters.
5. If instead, heat is transferred to the environment faster than thermal energy can be converted from chemical potential energy, then body temperature falls, possibly leading to hypothermia and cold-related injuries such as frost-bite. We will learn to prevent hypothermia by understanding how and when heat transfer to the environment can become too fast in the following chapters.

CHAPTER 89.

MEASURING BODY TEMPERATURE

LIQUID THERMOMETERS

We now know that an increase in temperature corresponds to an increase in the average kinetic energy of atoms and molecules. A result of that increased motion is that the average distance between atoms and molecules increases as the temperature increases. This phenomenon, known as thermal expansion is the basis for temperature measurement by liquid thermometer.



A clinical thermometer based on the thermal expansion of a confined liquid. Image Credit: Clinical Thermometer by Menchi via Wikimedia Commons

1

Common liquid thermometers use the thermal expansion of alcohol confined within a glass or plastic tube to measure temperature. Due to thermal expansion, the alcohol volume changes with temperature. The thermometer must be calibrated by marking the various fluid levels when the thermometer is placed in an environment with a known temperature, such as water boiling at sea level.

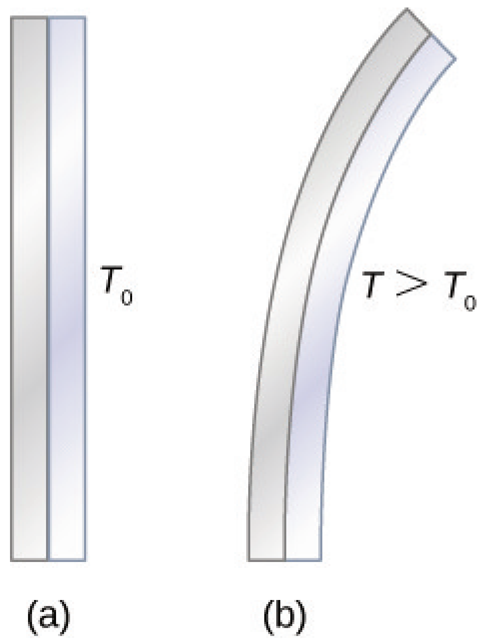
Reinforcement Exercise

BIMETALLIC STRIPS

Different materials will thermally expand (or contract) by different amounts when heated (or cooled). Bimetallic strips rely on this phenomenon to measure temperature. When two different materials are stuck together, the resulting structure will bend as the temperature changes due to the different thermal expansion experienced by each material.

An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=2749

1. Clinical Thermometer by Menchi [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)] via Wikimedia Commons



The curvature of a bimetallic strip depends on temperature. (a) The strip is straight at the starting temperature, where its two components have the same length. (b) At a higher temperature, this strip bends to the right, because the metal on the left has expanded more than the metal on the right. At a lower temperature, the strip would bend to the left. Image Credit: Openstax University Physics

[2]

LINEAR THERMAL EXPANSION

For most common materials the change in length $(DeltaL)$ caused by a change in temperature $(DeltaT)$ is proportional to the original length (L_0) and can be modeled using the linear thermal expansion coefficient (α) and the following equation:

(1) $\Delta L = \alpha L_0 \Delta T$

The following table provides the linear thermal expansion coefficients for different solid materials. More expansive (ha!) tables can be found online.

Thermal Expansion Coefficients

material	**coefficient of linear expansion (1/°c)**
Solids	
Aluminum	25×10^{-6}
Brass	19×10^{-6}

2. OpenStax University Physics, University Physics. OpenStax CNX. May 10, 2018 http://cnx.org/contents/74fd2873-157d-4392-bf01-2fccab830f2c@5.301.

material	coefficient of linear expansion $(1/°C)$
Copper	17×10^{-6}
Gold	14×10^{-6}
Iron or steel	12×10^{-6}
Invar (nickel-iron alloy)	0.9×10^{-6}
Lead	29×10^{-6}
Silver	18×10^{-6}
Glass (ordinary)	9×10^{-6}
Glass (Pyrex®)	3×10^{-6}
Quartz	0.4×10^{-6}
Concrete, brick	$\sim 12 \times 10^{-6}$
Marble (average)	2.5×10^{-6}

Everyday Example

The main span of San Francisco's Golden Gate Bridge is 1275 m long at its coldest. The bridge is exposed to temperatures ranging from –15 **°C** to 40 **°C**. What is its change in length between these temperatures? Assume that the bridge is made entirely of steel.

We can use the equation for linear thermal expansion:

$$\Delta L = \alpha L_0 \Delta T$$

Substitute all of the known values into the equation, including the linear thermal expansion coefficient for steel and the initial and final temperatures:

$$\Delta L = 12 \times 10^{-6} \frac{1}{\mathbf{C}\circ} (1275\,\mathbf{m})\,(40\,^{\circ}\mathbf{C} - (15\,^{\circ}\mathbf{C})) = 0.84\,\mathbf{m}$$

Although not large compared to the length of the bridge, the change in length of nearly one meter is observable and important. Thermal expansion could causes bridges to buckle if not for the incorporation of gaps, known as expansion joints, into the design.

Expansion joint on the Golden Gate Bridge. Image Credit: Expansion Joint Golden Gate Bridge by Michiel1972 via Wikimedia Commons

3

Reinforcement Exercises

4

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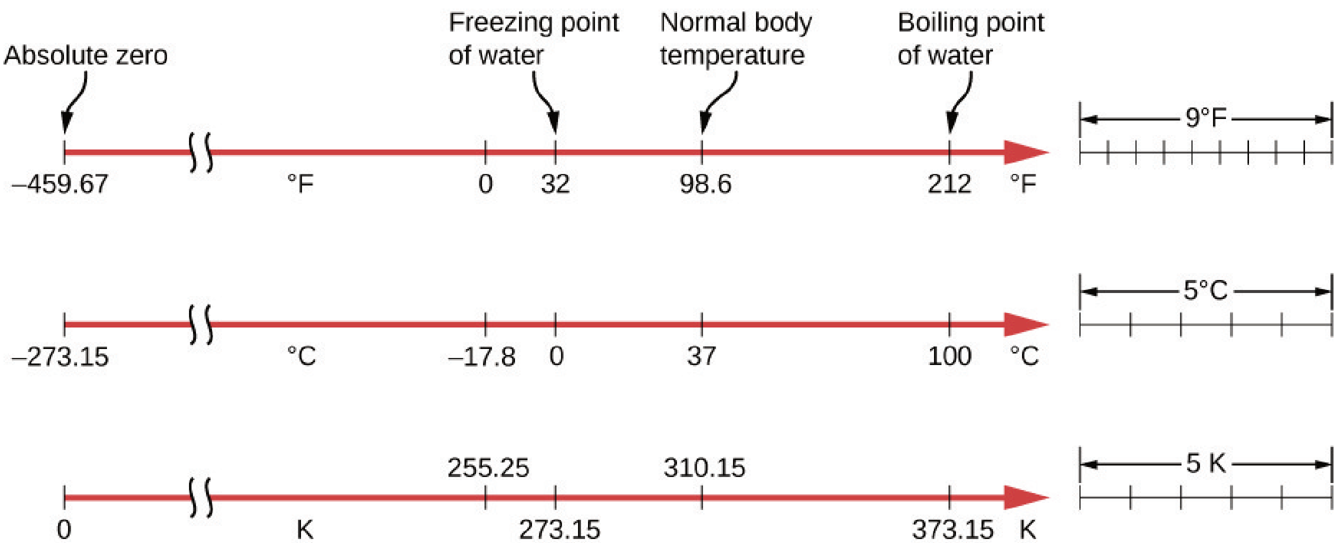
3. Michiel1972 [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons
4. "Web-based hypothermia information: a critical assessment of Internet resources and a comparison to peer-reviewed literature" by Dr. Eric Christian, Cosmicopia, NASA is in the Public Domain

TEMPERATURE UNITS

Thermometers measure temperature according to well-defined scales of measurement. The three most common temperature scales are Fahrenheit, Celsius, and Kelvin. On the Celsius scale, the freezing point of water is 0 **°C** and the boiling point is 100 **°C**. The unit of temperature on this scale is the degree Celsius (**°C)**. The Fahrenheit scale (**°F)** has the freezing point of water at 32 **°F** and the boiling point 212 **°F**. You can see that 100 Celsius degrees span the same range as 180 Fahrenheit degrees. Thus, a temperature difference of one degree on the Celsius scale is 1.8 times as large as a difference of one degree on the Fahrenheit scale, as illustrated by the top two scales in the following diagram.



Relationships between the Fahrenheit, Celsius, and Kelvin temperature scales are shown. The relative sizes of the scales are also shown. Image Credit: Temperature Scales diagram from OpenStax University Physics[/footnote]

THE KELVIN SCALE

The definition of temperature in terms of molecular motion suggests that there should be a lowest possible temperature, where the average microscopic kinetic energy of molecules is zero (or the minimum allowed by the quantum nature of the particles). Experiments confirm the existence of such a temperature, called absolute zero. An absolute temperature scale is one whose zero point corresponds to absolute zero. Such scales are convenient in science because several physical quantities, such as the pressure in a gas, are directly related to absolute temperature. Additionally, absolute scales allow us to use ratios of temperature, which relative scales do not. For example, 200 **K** is twice the temperature of 100 **K**, but 200 **°C** is not twice the temperature of 100 **°C**.

The Kelvin scale is the absolute temperature scale that is commonly used in science. The SI temperature unit is the Kelvin, which is abbreviated **K** (but not accompanied by a degree sign). Thus 0 **K** is absolute zero, which corresponds to -273.15 **°C**. The size of Celsius and Kelvin units are set to be the same so that differences in temperature (ΔT) have the same value in both Kelvins and degrees Celsius. As a result, the freezing and boiling points of water in the Kelvin scale are 273.15 **K** and 373.15 **K**, respectively, as illustrated in the previous diagram.

You can convert between the various temperature scales using equations or various conversation programs, including some accessible online.

Reinforcement Exercise

TEMPERATURE MEASUREMENT

In addition to thermal expansion, other temperature dependent physical properties can be used to measure temperature. Such properties include electrical resistance and optical properties such as reflection, emission and absorption of various colors. Light-based temperature measurement will come up again in the next chapter.

[5]

An interactive or media element has been excluded from this version of the text. You can view it online here:

https://openoregon.pressbooks.pub/bodyphysics/?p=2749

5. Significant content in this chapter was adapted from OpenStax University Phyiscs which you can download for free at http://cnx.org/contents/a591fa18-c3f4-4b3c-ad3e-840c0a6e95f4@1.322.

CHAPTER 90.

PREVENTING HYPOTHERMIA

HYPOTHERMIA

The Stages of Hypothermia

Stage	Core Body Temperature °C	Symptoms
Mild Hypothermia	35°-33°	shivering, poor judgment, amnesia and apathy, increased heart and respiratory rate, cold and/or pale skin
Moderate Hypothermia	32.9°-27°	progressively decreasing levels of consciousness, stupor, shivering stops, decreased heart and respiratory rate, decreased reflex and voluntary motion, paradoxical undressing.
Severe Hypothermia	< 26.9°	low blood pressure and bradycardia, no reflex, loss of consciousness, coma, death

[1]

THERMAL POWER

The rate at which chemical potential energy is converted to thermal energy by the body (and other systems) is the thermal power. When the thermal power is less than than the heat loss rate then the body will lose thermal energy over time and body temperature will drop. The only options for preventing hypothermia are slowing down the heat loss rate and/or increasing the thermal power. You can fight off hypothermia by doing additional work, such as jumping around, because the body is inefficient so most of the chemical potential energy used to do the work actually becomes thermal energy that can replace what was lost as heat. Shivering is your body's way of forcing you to take this approach and signifies a mild stage of hypothermia. However, this strategy will only be successful until you have used up your readily accessible supply of chemical potential energy. Basically, as you get tired this method will fail. The overall chemical to thermal energy conversion rate can be supplemented by technology such chemical hand/foot warmers and battery powered heated clothing, but in most situations will your body does the bulk of the conversion. Eventually these supplemental energy sources will also run out and body temperature will continue to drop. Moderate hypothermia is indicated by the end of shivering and increased mental confusion, possibly including hallucinations. Severe hypothermia leads to loss of consciousness and if not treated, eventually death.[2]

1. Adapted from "Web-based hypothermia information: a critical assessment of Internet resources and a comparison to peer-reviewed literature" by M Spencer, Jeremy & Sheridan, Scott, Perspectives in public health, 135(2) · February 2014

Everyday Example: Human Thermal Power

The typical daily intake of chemical potential energy required by the human body is 2000 Calories. A hard 8 hours of manual labor only accounts for 1/3 of a day and during the other 2/3 almost no useful work is done by the body so nearly all chemical energy being used is converted to thermal energy. Even when useful work is being done, the body is only about 25% efficient so most of the chemical energy used is still converted to thermal energy. Therefore we can reasonably approximate the thermal power ($< em > P_H$P_H" title="Rendered by QuickLaTeX.com" height="13" width="72" style="vertical-align: -2px;">) of the human body to be roughly 2000 Calories/day by assuming all chemical energy used eventually becomes thermal energy. Remembering that food Calories with a capitol C are actually **kcals** and that 4.186 Joules are in one calorie, we can use unit conversion to find the thermal power in SI units of Watts.

$$P_H = \left(\frac{2000\,\mathbf{Calories}}{1\,\mathbf{day}}\right)\left(\frac{1000\,\mathbf{cal}}{1\,\mathbf{Cal}}\right)\left(\frac{4.186\,\mathbf{J}}{1\,\mathbf{cal}}\right)\left(\frac{1\,\mathbf{day}}{24\,\mathbf{hrs}}\right)\left(\frac{1\,\mathbf{hr}}{60\,\mathbf{min}}\right)\left(\frac{1\,\mathbf{min}}{60\,\mathbf{s}}\right) \approx 100\,\mathbf{W}$$

PREVENTING HYPOTHERMIA

Your body loses heat to the environment due to a natural tenancy of systems to move toward thermal equilibrium. In fact the Second Law of Thermodynamics tells us that *objects left to themselves will always spontaneously trend toward thermal equilibrium with their environment*. For two objects to reach thermal equilibrium, heat must transfer away from the hot object and into the cold one so that their temperatures move closer together. Therefore, a consequence of the Second Law of Thermodynamics is that *heat will always spontaneously transfer from warmer temperature to colder temperature.* Homeostasis is a constant battle against the consequences of the Second Law of Thermodynamics. We aren't able to violate the second law of thermodynamics and stop or reverse the spontaneous thermal energy transfer away from the body in cold environments, we can only try to slow it down.

2. "Hypothermia and Cold Related Injuries" by J. Justad, MD, DDP, Health and Safety Guidelines, Montana Department of Health and Human Services

Reinforcement Exercises

HEAT TRANSFER

Materials designed to slow the heat transfer rate, or thermal insulation, can be used to help prevent hypothermia. There are three ways that heat is transferred out of the body, but all three methods follow the Second Law of Thermodynamics and transfer heat from warmer temperature to colder. The heat transfer mechanisms are:

1. ***Conduction***
2. ***Convection***
3. ***Radiation***

The following chapters will discuss these mechanisms and the types of insulation used to prevent each.

Everyday Examples: Insulation

My father was a bush pilot in Alaska. When I was about 13 years old we were landing on a lake in our hometown and found two teenagers clinging to their overturned canoe. The first boy had a stocky build and second was tall and thin. The first boy climbed onto the float and into the plane with some assistance, the thin boy was unable to move and was dragged out of the water just before losing consciousness as we rode back to shore. We later learned that the thin boy had reached the third stage of hypothermia and was likely only minutes from death. The thin boy had less body mass, thinner layers of tissue to provide insulation, and less chemical potential energy stored up for conversion to thermal energy. Both boys were wearing cotton clothing, which did not provide much insulating value in the water. In the following chapters we will learn how each of these factors contributed to the dramatically different in responses of the two boys to their unplanned cold water immersion.

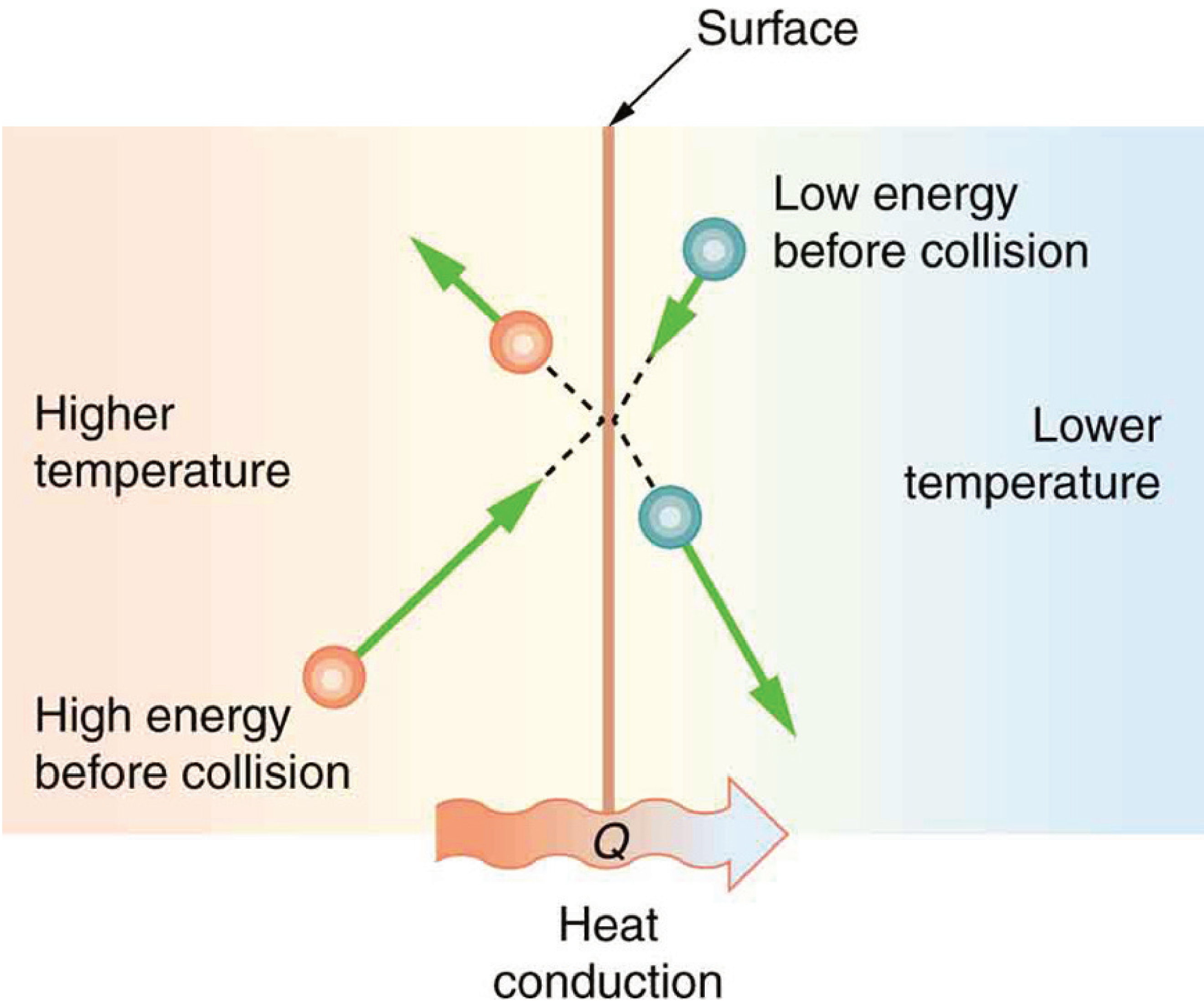
An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=1076

CHAPTER 91.

COTTON KILLS

CONDUCTION

Cotton is a great thermal insulator – as long as it's dry. Once wet, cotton becomes a poor insulator and does a poor job of preventing hypothermia-hence the old adage, "cotton kills". To understand why cotton is sometimes good insulator and sometimes a poor one, we need to understand conduction, which is the transfer of thermal energy between objects by direct contact. The average kinetic energy of the molecules in a hot body is higher than in a colder body. If two molecules collide, an energy transfer from the molecule with greater kinetic energy to the molecule with less kinetic energy occurs. The cumulative effect from many collisions occurring at a surface of contact between the two objects results in transfer of heat from the hot object to the colder object, (or colder environment) in agreement with the Second Law of Thermodynamics.



The molecules in two objects at different temperatures have different average kinetic energies. Collisions occurring at the contact surface tend to transfer energy from high-temperature regions to low-temperature regions, in agreement with the second Law of Thermodynamics. In this illustration, a molecule in the lower temperature region (right side) has low energy before collision, but its energy increases after colliding with the contact surface. In contrast, a molecule in the higher temperature region (left side) has high energy before collision, but its energy decreases after colliding with the contact surface.

CONTACT AREA

The number of molecular collisions increases with increasing contact area (A_c), so the rate of heat conduction depends on the contact area. More collisions, and thus more time, will be needed to transfer the same amount of heat across a thicker material, so heat transfer rate also depends on thickness, or length across which the heat is transferred (d). This model explains why thick clothing is warmer than thin clothing in winters, and why thin people are typically more susceptible to hypothermia.

TEMPERATURE DIFFERENCE

If the object temperatures are the same, the net heat transfer rate falls to zero, and thermal equilibrium is achieved. As the difference in temperature increases, the average kinetic energy transferred from fast to slow molecules during each collision also increases. Therefore the temperature difference also affects the rate of heat transfer by conduction.

THERMAL CONDUCTIVITY

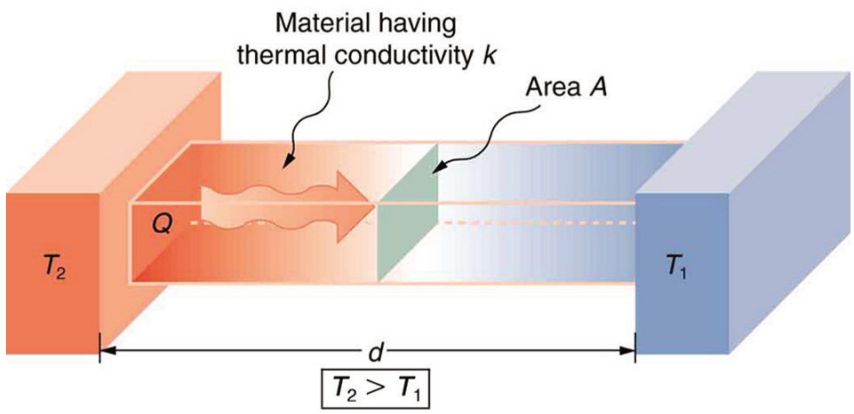
Lastly, some materials conduct thermal energy faster than others. In general, good conductors of electricity (metals like copper, aluminum, gold, and silver) are also good heat conductors, whereas insulators of electricity (wood, plastic, and rubber) are poor heat conductors. The effect of a material's properties on conductive heat transfer rate is described by the coefficient of thermal conductivity (k), which is sometimes shortened to just *thermal conductivity*. The following table shows values of k for some common materials in units of Watts, per meter, per Kelvin ($boldW/(boldmcdotK)$).

Thermal Conductivities of Common Substances

substance	**thermal conductivity ($boldfracW(mcdotK)$)**
Silver	420
Copper	390
Gold	318
Aluminum	220
Steel iron	80
Steel (stainless)	14
Ice	2.2
Glass (average)	0.84
Concrete brick	0.84
Water	0.6
Fatty tissue (without blood)	0.2
Asbestos	0.16
Plasterboard	0.16
Wood	0.08–0.16
Snow (dry)	0.10
Cork	0.042
Glass wool	0.042
Wool	0.04
Down feathers	0.025
Air	0.023
Styrofoam	0.010

CONDUCTION EQUATION

We can summarize all of the factors effecting the conductive heat transfer rate, which is an amount of energy transferred per time, in a single diagram:



Heat conduction occurs through any material, represented here by a rectangular bar, whether window glass or walrus blubber. The temperature of the material is T_2 on the left and T_1 on the right, where T_2 is greater than T_2. The rate of heat transfer by conduction is directly proportional to the surface area A, the temperature difference, and the substance's conductivity k. The rate of heat transfer is inversely proportional to the thickness d.

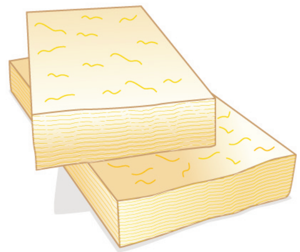
The rate of heat transfer across a material with temperature T_1 on one side and temperature T_2 on the other can be modeled by the conduction equation:

$$\frac{Q}{t} = \frac{kA(T_2 - T_1)}{d} \quad (1)$$

The rate of heat transfer (Q/t)refers to an amount of energy transferred per unit time so it has the same units as power (P). The term power is usually applied to a rate of transformation of energy from one form to another, but heat is a transfer of thermal energy from one place another, not a change in type of energy, thus we stick with $fracQt$ instead of P as the notation for this rate. This notation also reminds us that if we want to know how much energy was transferred during a certain time, we need to multiply the heat rate by the time.

INSULATION TECHNOLOGY

We can see from the conduction equation that combining thickness (loft) with low conductivity provides the greatest insulating effect. Goose down is the gold-standard insulation clothing for extreme-cold environments because it recovers loft after being compressed and it has low conductivity. As with most insulating materials, the effectiveness of down at reducing conduction is not due to the low conductivity of the feathers themselves, but rather their ability to trap air which has a very low conductivity. Double-pane windows, Styrofoam, animal hair, and the fiberglass insulation used in buildings all rely on this same strategy of trapping air to provide insulation.



The fiberglass batt is used for insulation of walls and ceilings to prevent heat transfer between the inside of the building and the outside environment.

Everyday Example: Down Insulation

Let's compare the insulating properties of a cotton sweatshirt and a down jacket, such as the one worn in the photograph below.

The author approaches the summit of Mt. Washington in the Central Oregon Cascades, in snowstorm, but wearing a down jacket. February 2017.

We will start with the conduction equation:

$$\frac{Q}{t} = \frac{kA(T_2 - T_1)}{d}$$

The outside temperature was about $-10\,^{\circ}\mathbf{C}$ and skin temperature is roughly $37\,^{\circ}\mathbf{C}$, so the temperature difference was about $47\,^{\circ}\mathbf{C}$. When dry, the down jacket pictured is roughly $4\,\mathbf{cm}$ thick, which $0.04\,\mathbf{m}$. The thermal conductivity of dry down is roughly $0.025\,\frac{\mathbf{W}}{\mathbf{m \cdot K}}$. Using the methods in Chapter 17 we estimate the surface area of the upper body to be $0.5\,\mathbf{m}$. Entering these values into the equation we find:

$$\frac{Q}{t} = \frac{(0.025\,\mathbf{W}/(\mathbf{m}\cdot\mathbf{K}))(0.5\,\mathbf{m^2})(47\,\mathbf{C}^{\circ})}{0.04\,\mathbf{m}} \approx 15\,\mathbf{W}$$

So heat loss rate through the upper body in this situation is 30 **W**. That means 15 **J** of thermal energy is released to the environment as heat through the upper body each second. The typical human thermal power is 100 **W** so it appears that there is plenty of thermal energy available to maintain temperature. However, the 15 **W** value we found does not account for heat loss from the lower body, which we can see from the picture were not covered with down. In fact the single thin layer worn on the legs easily allowed for the other 85 **W** to escape so that body temperature was not elevated. In fact, doing the extra work of climbing the mountain likely raised the the thermal power closer to 300 **W** so actually something closer to 285 **W** was being exhausted through the lower body. As a result, body temperature dropped quickly when climbing stopped and the thermal power fell back to about 100 **W**.

If the down were to get wet, things would change drastically. The down would lose its loft and end up with roughly 0.5 **cm** thickness. Even worse, the water would fill in the air spaces between the down fibers so the thermal conductivity would essentially be the same as for water, which is $0.6\,\frac{\mathbf{W}}{\mathbf{m \cdot K}}$. Entering these values into the conduction equation we find:

$$\frac{Q}{t} = \frac{(0.6\,\mathbf{W}/(\mathbf{m}\cdot\mathbf{K}))(1\,\mathbf{m^2})(47\,\mathbf{C}^{\circ})}{0.01\,\mathbf{m}} \approx 5600\,\mathbf{W}$$

Now that's a problem. The wet heat loss rate is nearly 190x faster than for the dry down in this situation, so to keep up we would need to eat 188 candy bars every six hours, or 31 candy bars per hour! Our bodies would not be able to digest and convert chemical potential energy to thermal energy fast enough to keep warm in that situation and eventually hypothermia would occur. Later in this unit we will be able to estimate how long it would take for the body temperature to drop to dangerous levels in this situation. Down is clearly a poor insulator when wet, but even after drying the fibers do not naturally recover their original loft. Down is a poor choice of insulation in wet environments, though it does well in snow storms as long as the air temperature is cool enough that the snow doesn't melt when it lands on the jacket.

Everyday Examples: Cotton Kills

Just as with down, water can permeate the spaces between other fabrics like wool, synthetics, and cotton. The majority of water can be wrung out of wool and synthetics, partially restoring their insulating properties and helping them to dry out quickly and recover full insulation value. In the other hand, water fills space between cotton fibers and also saturates the fibers themselves. As a result cotton does not wring out well and dries slowly, so its thermal conductivity remains much closer to that of water than wool or synthetic. Cotton is a poor choice of insulation in wet environments.

Reinforcement Exercise: Single Pane Windows

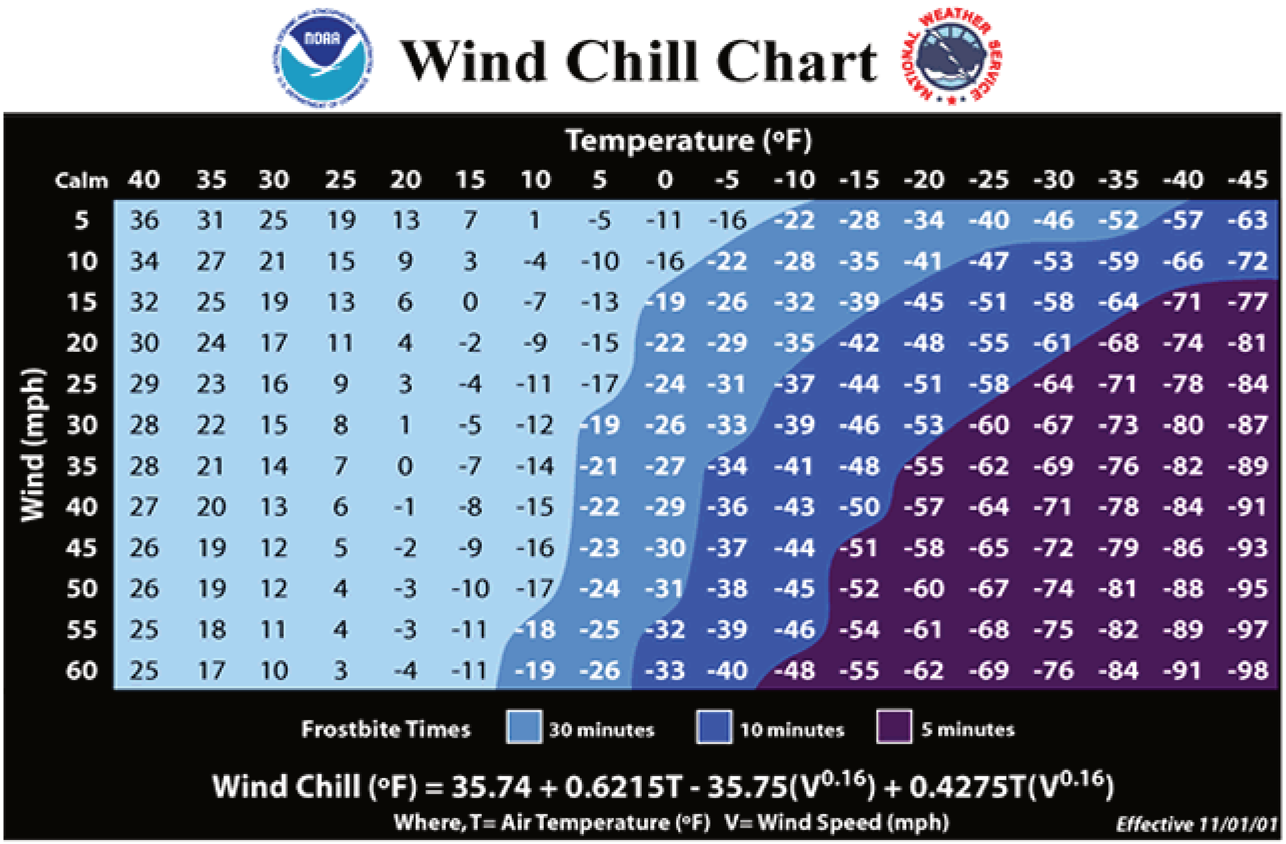
Significant content in this chapter, including the table of conductivities, was adapted from College Physics, by BC Open Textbooks [1]

An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=2780

1. "Conduction" by College Physics, BC Open Textbooks is licensed under CC BY 4.0

CHAPTER 92.

WIND-CHILL FACTOR



Wind Chill Chart

Temperature (°F)

Wind (mph) Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72
15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81
25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91
45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93
50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95
55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98

Frostbite Times: 30 minutes, 10 minutes, 5 minutes

$$\text{Wind Chill (°F)} = 35.74 + 0.6215T - 35.75(V^{0.16}) + 0.4275T(V^{0.16})$$

Where, T= Air Temperature (°F) V= Wind Speed (mph)

Effective 11/01/01

The wind chill chart displays the theoretical calm air temperature which would produce the same cooling rate as the actual air temperature + wind combination. Image Credit: "Wind Chill Chart" by National Weather Service, NOAA

[1]

As stiff breeze can feel refreshing on a hot day and make a cool day feel quite cold. This phenomenon is known as the wind chill effect or just *wind chill*. Wind chill is a significant factor in thermal injuries such as hypothermia and frost bite, which is tissue damage caused by the formation of ice crystals within the tissue. The wind chill chart above shows what calm air temperature would be necessary to produce the same heat loss rate as the actual air temperature plus wind combination.

1. "Wind Chill Chart" by National Weather Service, NOAA is in the Public Domain

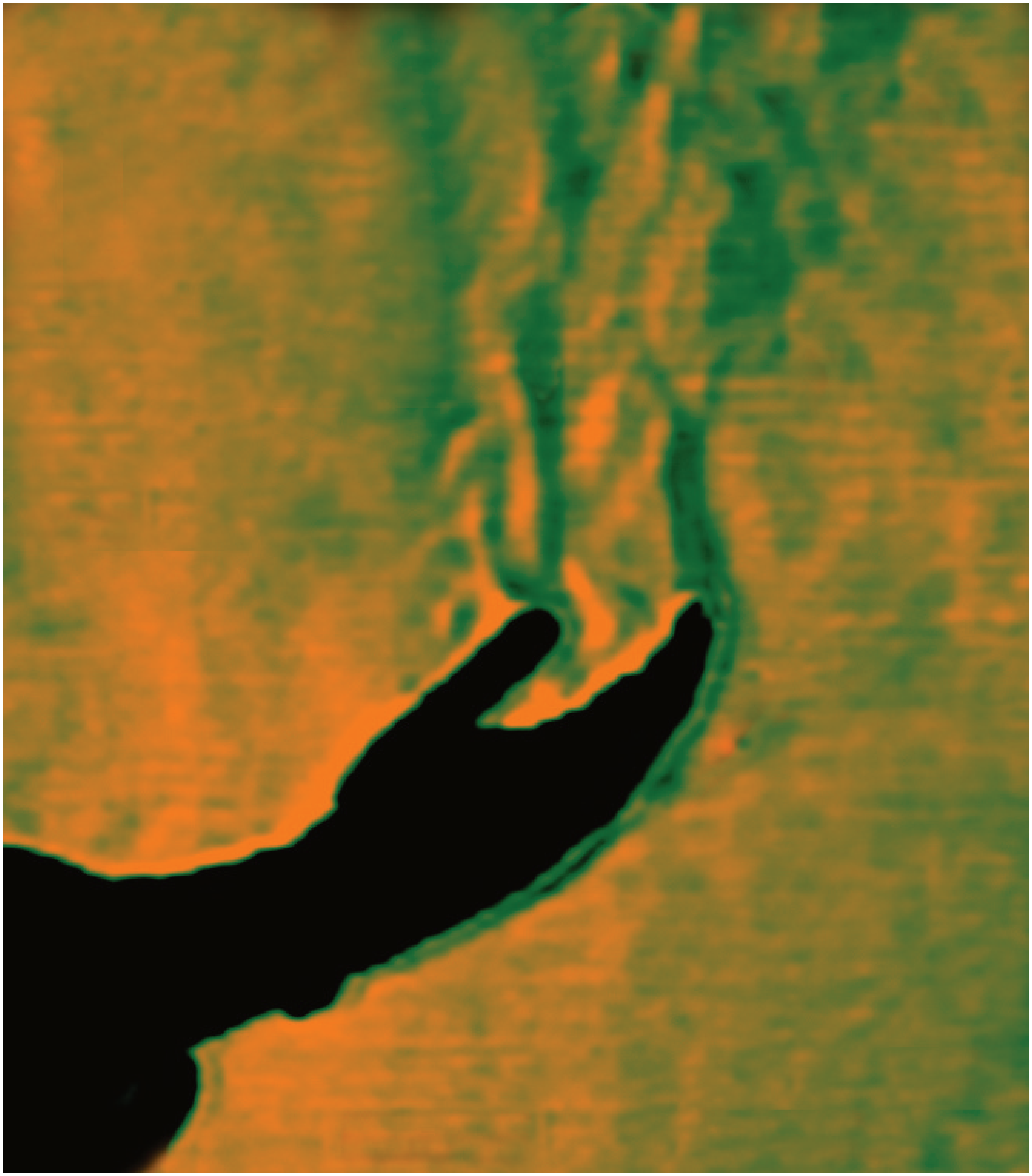
The chart is makes this calculation specifically for the skin on a human face. The chart also shows the exposure time which is likely to result in frostbite. For example, a day with 10 °**F** air temperature and 10 **mph** wind would feel as cold as a -7 °**F** day without wind.

Everyday Example

The author grew up in a small remote town on the tundra in Western Alaska. School was cancelled on days when the wind chill was less than -75 **°F.** According to the windchill chart, school could be cancelled on a -30 **°F** day with 55 **mph** wind or on a -45 **°F** day with 15 **mph** wind. Both of these combinations were entirely possible in Bethel, Alaska and growing up we usually had one or two wind chill cancellation days per year.

FORCED CONVECTION

In the absence of wind, a layer of warm air will form next to your skin, which effectively provides an additional layer of insulation known as a boundary layer. The thermal image below color-codes warm and cool air so that we can visualize the formation of the warm boundary layer. (In the next chapter we will learn how thermal images like this one are created.)



Thermal image showing air (green) warmed by conduction from the skin then rising within the surrounding cooler and more dense air due to natural convection, which is discussed in the following section. Forced convection is the reduction of this boundary layer by fluid due to factors other than the warming of the fluid itself, such as wind. Image Credit: "Thermal Plume from human hand" by Gary Settles via Wikimedia Commons

2

We can see that the skin-warmed layer is thin, but air has a very low thermal conductivity, so this layer can make and important contribution to slowing conduction. Wind tends to partially strip this insulating layer away and replace it with cooler air. The thickness of the warm boundary layer that is able to form depends on the wind speed, with higher speeds leading to thinner layers and causing greater wind chill effect. Wind chill is an example of forced convection, in which warm and cold fluid exchange places due to fluid motion caused by external factors such as blowing wind or flowing water.

Everyday Example: Hot Springs and Saunas

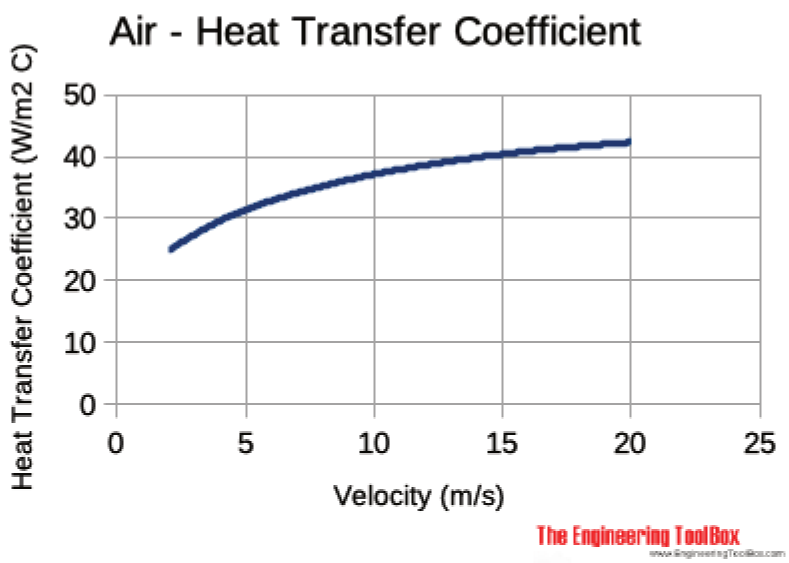
When submerged in fluid with a temperature higher than body temperature, such as in a hot spring or sauna, you may notice that the fluid suddenly feels hotter when you move around. Whether a fluid moves around you, or you move through the fluid, forced convection will occur in either case. When the fluid is warmer than your body then heat transfers out of the fluid into your body, leaving a slightly cooler boundary layer of fluid next to your skin. When you move this boundary layer gets left behind and replaced with new hot fluid that has not yet been cooled down by your body.

The rate of heat transfer by forced convection can be calculated using an empirical equation that looks very similar to the conduction equation:

(1) $Q/t = hA(T_2 - T_1)$

Once again the heat transfer rate is proportional to a difference between the object and environment temperatures. Contact surface area (*A*), again plays a role, in this case between the object and the fluid. Finally the convective heat transfer coefficient (*h*) incorporates fluid properties and accounts for the dependence of boundary layer thickness on fluid speed. The convective heat transfer coefficient is often determined experimentally. For example, the following graphs shows experimental data on the heat transfer coefficient for air at a range of wind speeds:

2. "Thermal Plume from human hand" by Gary Settles [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], from Wikimedia Commons



Graph of convective heat transfer coefficient data for air. The "m2" in the units of the vertical axis means square meters.

3

Reinforcement Exercises

Everyday Example: Cold Weather Survival

Cutting down on wind chill (forced convection) is an important part of the overall cold weather survival strategy. Let's evaluate the effects of forced convection during a wilderness survival situation at 25 **°F** (-3.9 **°C**) with a 10 **mph** (4.5 **m/s**) wind. Let's assume you are wearing thin fabrics that are fairly permeable to wind. Now we can approximate the effect of convection by assuming the fabric surface is the same as body temperature and applying the convection equation:

$$Q/t = hA(T_2 - T_1)$$

An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=2790

3. Engineering ToolBox, (2003). *Convective Heat Transfer*. [online] Available at: https://www.engineeringtoolbox.com/convective-heat-transfer-d_430.html [Accessed 18 1. 2019]

The difference between body temperature and the air temperature is 37 **°C** – (-3.9 **°C**) = 40.9 **C°**. The heat transfer coefficient is about $27, boldfracWm^2cdotK$ according to the previous graph. Using the methods in Chapter 17 we estimate the surface of the upper body to be $1, boldm$. Entering these values into the convection equation:

$$Q/t = (27\,\frac{\mathbf{W}}{\mathbf{m^2}\cdot\mathbf{K}})(1\,\mathbf{m^2})(40.9\,\mathbf{C}^{\circ}) \approx 1100\,\mathbf{W}$$

The convective heat loss rate in this situation would completely overwhelm the 100 **W** resting thermal power of a typical person and body temperature would drop quickly. To see how quickly, check out the H*eat Capacity* chapter. Shivering can boost the thermal power by up to 2.5 times, to rougly 250 **W**[4], but even that would fall well short of balancing the convective heat loss rate. Finding shelter from the wind is an important part of the survival strategy. Carrying wind-stopping clothing is an important part of being prepared in the wilderness. Even a large plastic trash bag that could be worn over most of the body would significantly cut down on heat loss by convection.

NATURAL CONVECTION

Wind will not penetrate a well-sealed window, so it seems like forced convection should not be a significant factor in the heat loss through a window. However, a single pane of glass does a poor job of preventing conduction, so significant thermal energy still crosses the barrier. That thermal energy will warm up a boundary layer on the outside of the window, which could then be stripped away by wind, so in fact wind chill may affect the rate of heat loss through the window. Double pane windows reduce conduction by using a layer of trapped air between two panes of glass.

A diagram showing two glass panes separated by a gap filled with a gas. Arrows indicate that conduction occurs across the glass panes from right to left. Arrows indicate that a convection cell has formed in the gap, with gas rising on the right and falling on the left.

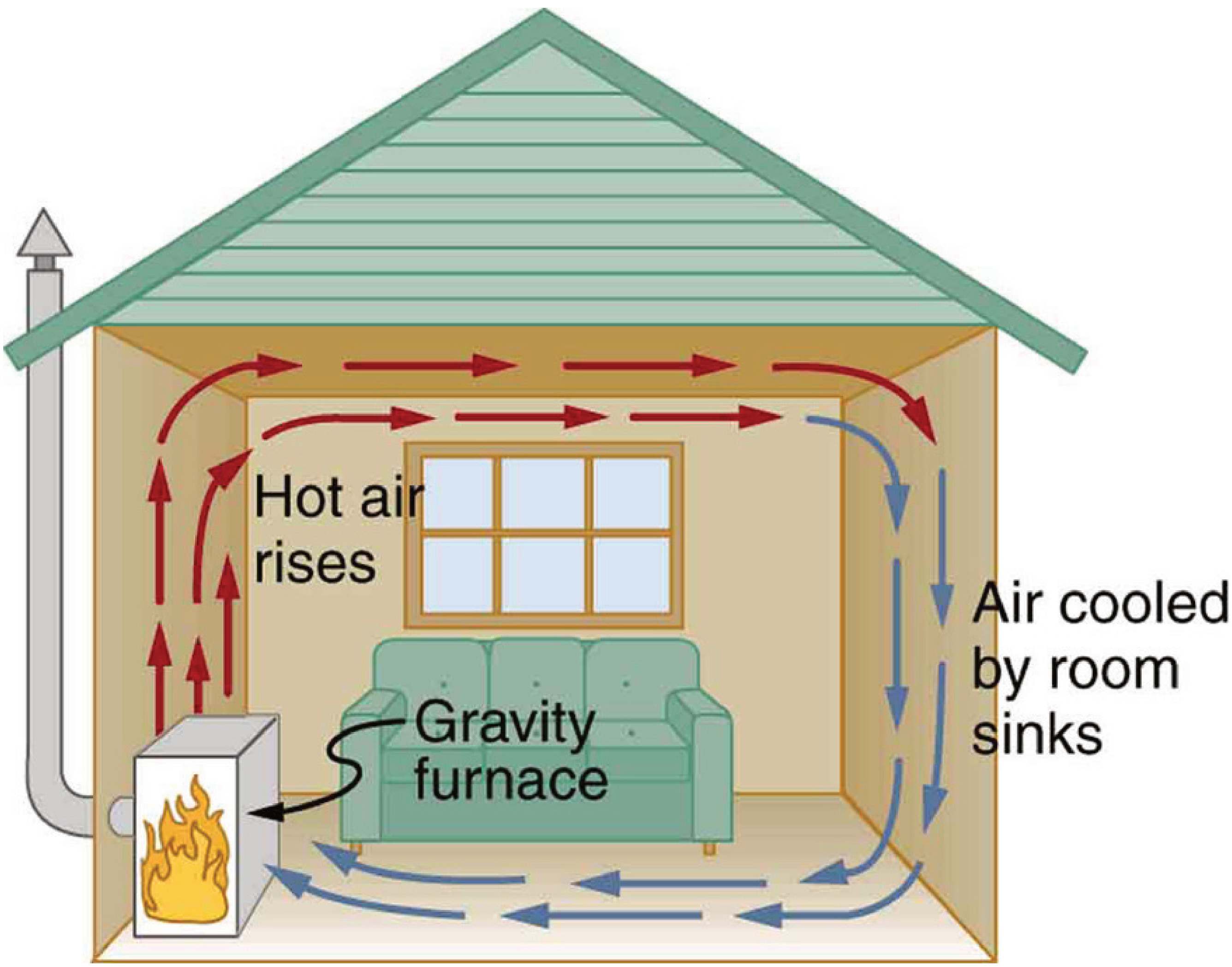
The gap within a double pane window is too small for efficient convection cells to form. Filling the gap with a less conductive, more viscous (or slow-moving) and low pressure gas further reduces both conduction and convection through the gas. A mixture of krypton and argon gases is often used as a compromise between thermal performance and cost. Image Credit: "Gas Filled Windows" by John A Dutton e-science Institute, Penn State College of Earth and Mineral Sciences

5

4. "Nutritional Needs In Cold And In High-Altitude Environments: Applications for Military Personnel in Field Operations" byAndrew J. Young, Michael N. Sawka and Kent B. Pandolf, National Center for Biotechnology Information, National Institutes of Health
5. "Gas Filled Windows" by John A Dutton e-science Institute, Penn State College of Earth and Mineral Sciences is licensed under CC BY-NC-SA 4.0

We know that conduction is reduced across a double pane window because the thermal conductivity of air is exceptionally low, but the air gap in a double pane windows is typically only about 2 **cm.** Considering that the rate of heat transfer by conduction decreases as the thickness of the air layer increases, why don't double pane windows have a much larger gap? Why not minimize conduction by making the gap almost the full thickness of the wall? Natural convection is the answer to that question. Natural convection is transfer of heat due to fluid movement caused by thermal expansion of the fluid itself, rather than by external factors such as wind. For example, you warm the air next to your skin and that air expands. After expanding, that same mass of air now has a larger volume, thus by definition it has a lower density. Being less dense than the surrounding cooler air, the warm air will float upward, as you can see in the previous thermal image of a person's hand. (To remind yourself why the warmer and less dense air will rise, see the earlier chapter on buoyant forces).

As the warmed air rises away from the skin it is replaced by cool air moving in from each side of the warm surface, which is then warmed before rising, creating a cyclic flow pattern known as a convection cell. Overall the convection cells transport thermal energy away from the skin (or any warm object).



A convection cell powered by thermal energy input from a furnace transfers thermal energy throughout a room. Unfortunately most of the warm air is the top half of the room, not near the bottom half where people usually hang out. Image Credit:OpenStax, College Physics

[6]

Using double pane windows with a large air gap would allow for large convection cells to form and those cells would efficiently transfer thermal energy across the gap. Keeping the gaps size small prevents large convection cells from forming.

Everyday Examples: Down, double-pane windows, fiberglass and fur

Most insulation strategies create a fiber matrix that traps small pockets of air exploit the low thermal conductivity while preventing large convection cells from forming. Down, fiberglass batting, and fur are examples of this strategy. The fibers of these materials have conductivity greater than air, so trapping more air with fewer fibers provides the lowest overall average conductivity. In fact, some animals, such as polar bears, have hollow fur to increase the ratio of air to matrix material.[7] The best insulation strategies combine an air trapping matrix to minimize conduction and natural convection with a wind-stopping outer coating to prevent forced convection. In wet climates the wind-stopping layer should also be water proof to prevent water from filling the air pockets created by the underlying fiber matrix.

WIND POWER

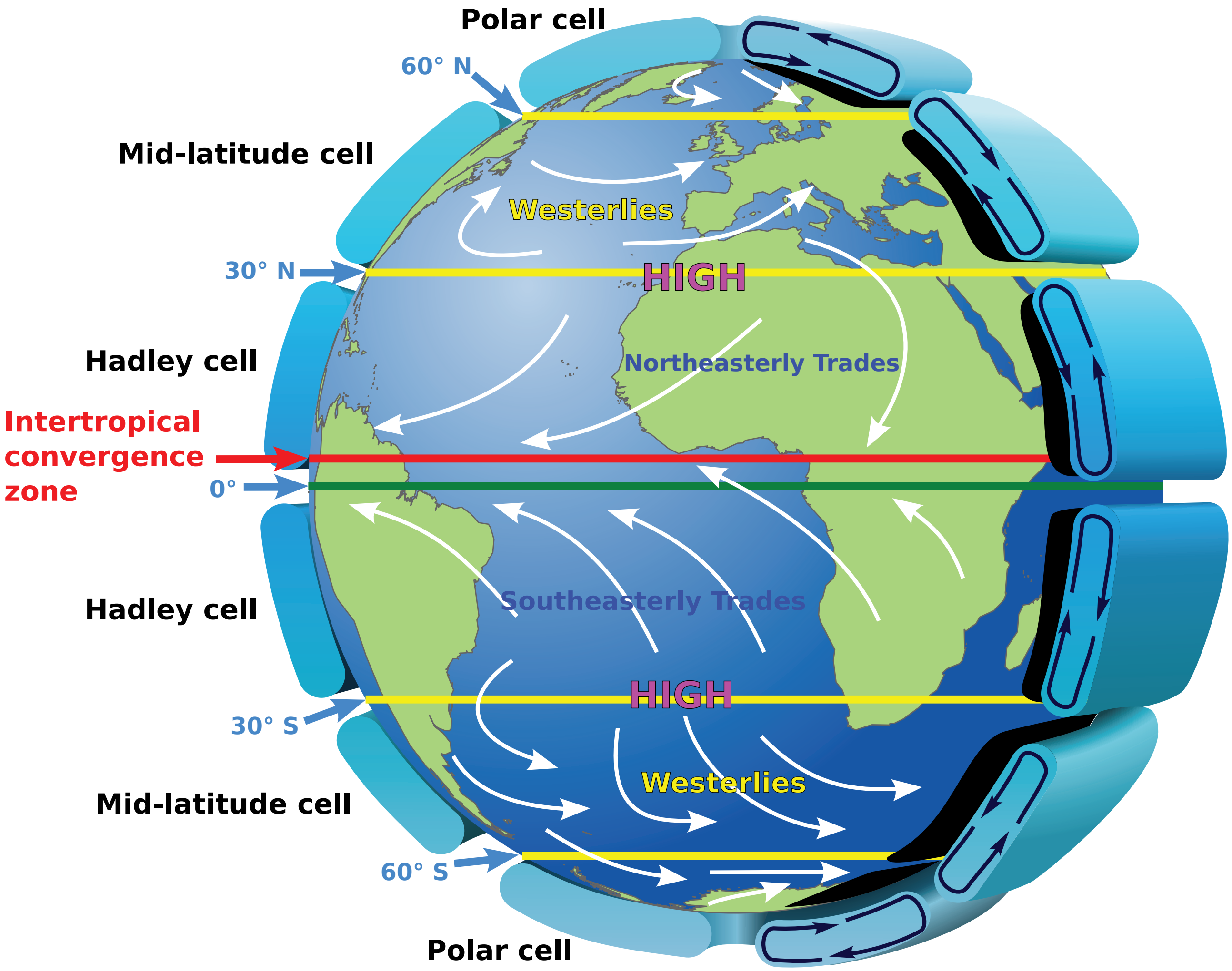
Convection cells drive heat transfer in a wide variety of systems on many scales. In fact the wind that serves to drive forced convection from your body is actually caused by natural convection cells. Such cells can form due to differential heating and cooling of the local geography. For example, the air above the ocean may remain cooler while the air above the coast warms rapidly during the day, resulting in an on-shore breeze (sea breeze) during the day. The convection cell reverses at night, creating an offshore breeze.

Reinforcement Exercises

Draw the convection cells near a coastline both during the day and at night in order to show how on-shore and off-shore breezes are created by differential heating of ocean and coastline. Indicate the relative temperature of the water, land and air during day and night.

Wind is also produced by global scale convection cells. The following graphic shows the global-scale convection cells that drive the winds at various latitudes. Notice that the spinning of the Earth combined with the inertia of the air mass creates a Coriolis Effect, which causes the wind direction to curve away from the direction indicated at the bottom of the convection cell. You may notice that the latitudes of the great deserts and forests of the world match up with the boundaries between the cells. We will learn why in the next chapter.

6. OpenStax, College Physics. OpenStax CNX. Nov 8, 2018 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@14.4
7. "Is Polar Bear Fur Transparent?" by Everyday Mysteries, The Library of Congress is in the Public Domain



Global convection cells and associated winds. Image Credit:

8

The predictability and stability of large scale convection cells allows for the growing implementation of wind turbine power plants. As our predictive skills continue to improve, along with turbine efficiency and energy storage technology, wind power is becoming a viable option for some communities.

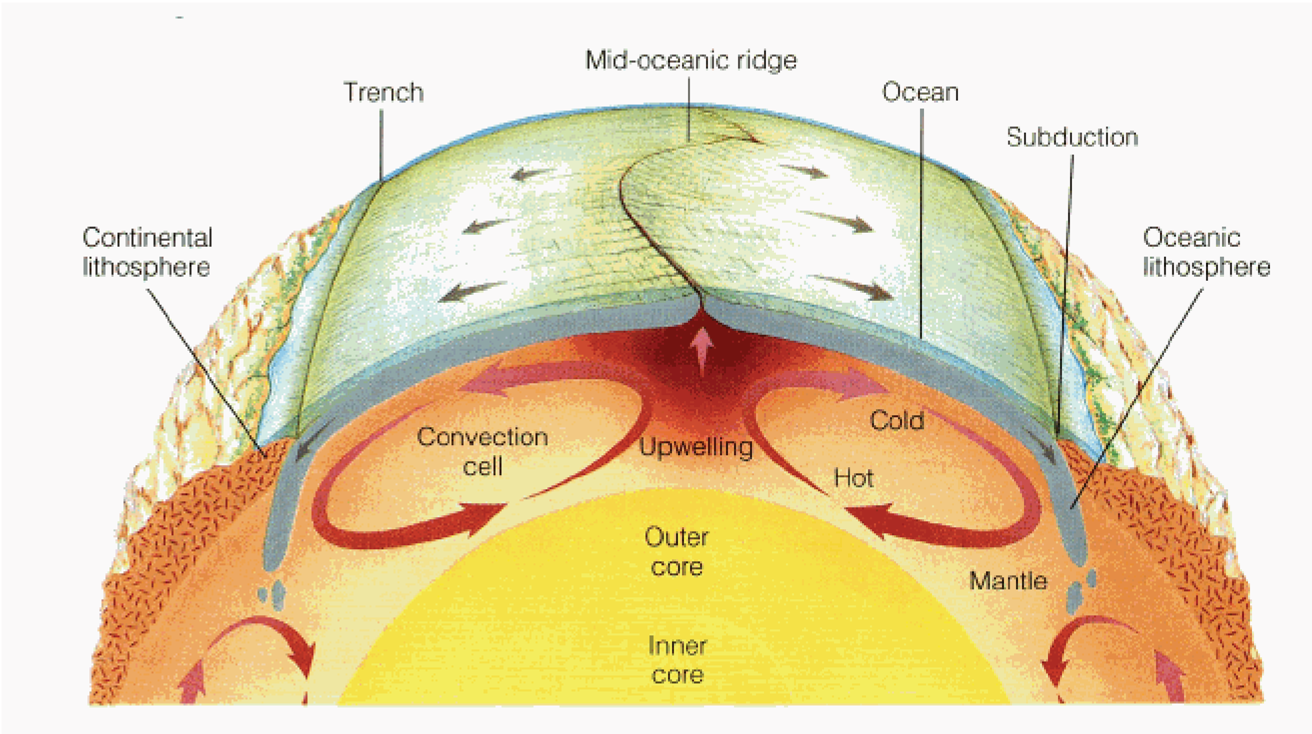
8. Earth Global Circulation-en by Kaidor [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons

Burbo Bank Offshore Wind farm with North Wales in the background. Image credit: Burbo Bank offshore WindFarm by Ian Mantel via Wikimedia Commons

9

Convection cells are even responsible for moving the continents:

9. Burbo Bank Offshore WindFarm by Ian Mantel [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], via Wikimedia Commons



Annotated illustration showing mantle convection and its relation to plate tectonics. Image Credit: Mantle Convection by Byrd Polar Research Center at Ohio State University, via the Science and Education Resource Center at Carlton College.

CHAPTER 93.

SPACE BLANKETS

U.S. Army Pfc. Robbin M. Chambers, a driver for 2nd Platoon, Alpha Company, 2nd Battalion, 162nd Infantry, 41st Infantry Brigade Combat Team, Oregon Army National Guard, opens a space blanket during a training exercise Oct. 24, 2014 in Kabul, Afghanistan.

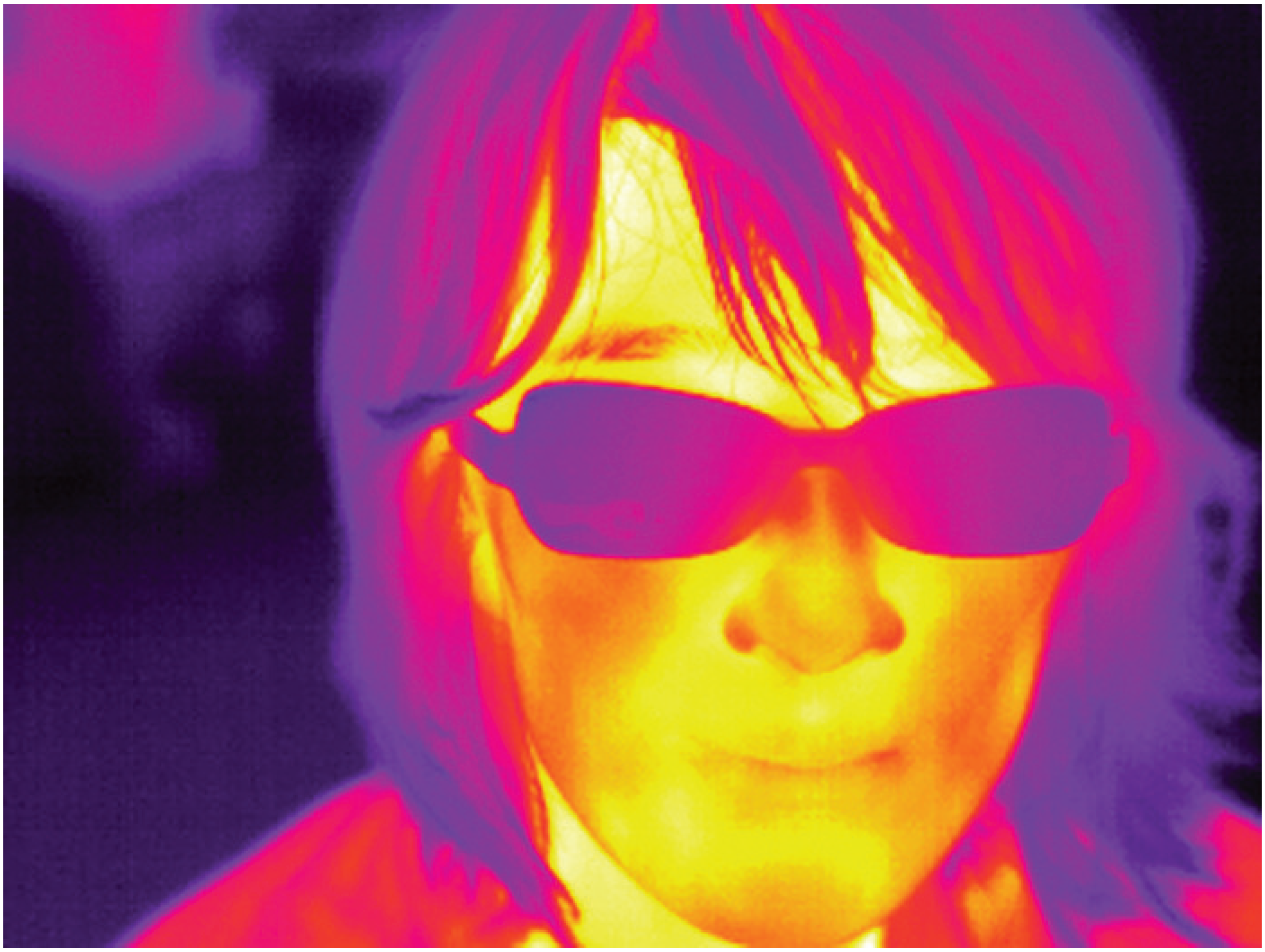
[1]

THERMAL RADIATION

Space blankets, (a.k.a survival blankets) such as the one seen in the previous image, are very thin and have a thermal conductivity roughly 5x greater than air[2], therefore they are a poor a preventing heat

1. "Oregon Soldiers complete medical training" by Capt. Leslie Reed, U.S. Army National Guard is in the Public Domain
2. "Mylar Product Information" by DuPont Teijin Films

loss by conduction. However, they do significantly reduce heat transfer by thermal radiation, which is the spontaneous emission of electromagnetic radiation by objects with temperature above absolute zero (so everything). Electromagnetic radiation sounds like a big deal, but its really just the descriptive scientific way to say *light waves*. Depending on the temperature of the object, the emitted light may not be visible to us, but it's there nonetheless. For example, your body emits thermal radiation that we cannot see, but thermal imaging cameras can detect such light and allow us to "see" objects that are at a different temperature from their environment even when no external light source is present.



Thermograph of a persons face produced by a thermal imaging camera. The camera represents the intensity and color of detected thermal radiation that humans can't see with variations in visible color to create a false-color image. The actual light emitted by the person and detected by the thermal imaging camera has a color that we cannot see. Image Credit: "Self Portrait with Thermal Imager" by Nadya Peek via Wikimedia Commons

[3]

Space blankets reflect the electromagnetic radiation emitted by your body back to you, rather than letting it escape, thereby reducing the rate at which your body loses thermal energy to the environment. Thermal radiation transfer is the reason why clear nights feel colder than cloudy ones

3. "Self Portrait with Thermal Imager" by Nadya Peek [CC BY 2.0 (https://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons

and why you frost forms on top of your car, but not on the ground beneath it. In order to explain these observed phenomenon and quantify heat loss from your body, we need to take a deeper look at thermal radiation.

STEPHAN-BOLTZMANN LAW

Some materials are more efficient at converting thermal energy to light than others and this material property, known as the emissivity ($epsilon$), affects the thermal radiation power (P_{out}). The radiated power also depends on the object's surface area (A) and temperature in Kelvin (T_o). The Stephan-Boltzmann Law relates the radiated power to all of these variables and the Stephan-Bolztmann constant ($\sigma = 5.67 \times 10^{-8}\,\mathbf{W/(mK^4)}$):

(1) $P_{out} = \sigma \epsilon A T_o^4$

Materials which are good at converting thermal energy into light will also be good at the reverse process of absorbing light and converting it to thermal energy in the material. As a result, the rate of heat transfer into an object by radiation ($P_{in} < em >$" title="Rendered by QuickLaTeX.com" height="13" width="75" style="vertical-align: -2px;">) can also be modeled using the Stephan-Bolztmann Law with the same emissivity value, only the incoming radiation power is determined by the temperature of the environment (T_{env}) rather than the object.

(2) $P_{in} = \sigma \epsilon A T_{env}^4$

Exercises

NET THERMAL RADIATION RATE

Subtracting the emitted radiation power from the absorbed radiation power we can determine the net radiation power to the object:

(3) $P_{net} = \sigma \epsilon A (T_{env}^4 - T_o^4)$

Notice that when the object is warmer than its environment, P_{net} will be negative because more radiation will be leaving the object than is absorbed.

Everyday Example: Space Blankets

Let's evaluate the effectiveness of adding a space blanket during the wilderness survival example from the previous

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https://openoregon.pressbooks.pub/bodyphysics/?p=2788

chapter. The situation was a 25 **°F** (-3.9 **°C**) day with a 10 **mph** wind and you are thin clothes that don't stop the wind very well. Layering the space blanket on top should cut the wind, so right off the bat you save most of the 1100 **W** of heat loss rate due to forced convection (wind chill effect) that we calculated in the last chapter. The blanket will reduce conduction somewhat by trapping a layer of air, but natural convection within that layer will move heat to the blanket where it will be conducted across, so you still experience much of the 160 **W** conductive heat loss we calculated previously.

A space blanket would effectively eliminate the thermal radiation heat loss by reflecting your emitted radiation back to you. Even though you will still transfer thermal energy to the inside of the blanket by conduction and natural convection from the inside, the blanket will do a poor job of radiating that energy away to outside because it has a relatively low emissivity.

Let's figure out your heat loss rate without the space blanket in order to see what heat loss it actually saves you. To make the calculation easier, let's assume a there is a layer of low clouds or heavy forest vegetation so that very little of the cold upper atmosphere is visible. In that case, the overall environmental temperature is just the -3.9 **°C** air temperature. We know body temperature 37 **°C** , but before we can calculate the net heat loss due rate to thermal radiation we must convert our temperatures to Kelvin:

$$T_{env} = -3.9\,^{\{}\mathbf{circ}C + 273.15 = 269.25\,\mathbf{K} T_o = 37\,^{\{}\mathbf{circ}C + 273.15 = 310.15\,\mathbf{K}$$

Now we can work to apply the Stephan-Boltzmann Law for net radiation power:

$$P_{net} = \sigma \epsilon A (T_{env}^4 - T_o^4)$$

Using the methods in Chapter 17 we estimate the surface area of the upper body to be $\approx 1\,\mathbf{m^2}$. The typical emissivity of human skin is 0.985[4]

$$P_{net} = (5.67 \times 10^{-8}\,\mathbf{W}/(\mathbf{mK^4}))(0.985)(1\,\mathbf{m^2})(269.25^4 - 310.15^4) \approx 200\,\mathbf{W}$$

We find that the rate of radiative heat loss would be approximately 200 **W** without a space blanket. Therefore the space blanket saves you 200 **W** of radiative heat loss and 1100 **W** of convective heat loss, leaving only the 160 **W** of conductive heat loss. We see that a space blanket can significantly reduce heat loss rate is some situations. Considering this benefit compared to its small weight and volume, a space blanket seems like a reasonable addition to a survival kit. However, *a space blanket will not serve as a substitute for appropriate clothing*. A typical person has a resting thermal power of roughly 100 **W**, therefore the person in our example would still have a 60 **W** thermal power deficit. Over time resulting energy loss would lower the body temperature until hypothermia triggered a shivering response, which could boost the thermal power by up to 2.5 times, or up to 250 **W**.[5] This strategy would only work short term, until the person was too tired to shiver. Alternatively, if the person in this example had gotten wet while wearing cotton then the resulting rate of heat loss by conduction would be roughly 1100 **W** (calculated in the *Cotton Kills* chapter) and shivering would not be able to make up for the thermal power deficit, even in the short term. Even shivering would not significantly delay a dangerously low body temperature in the wet cotton situation.

4. "Table of Emissivity of Various Surfaces" by Mikron Instrument Company, Inc.
5. "Nutritional Needs In Cold And In High-Altitude Environments: Applications for Military Personnel in Field Operations" byAndrew J. Young, Michael N. Sawka and Kent B. Pandolf, National Center for Biotechnology Information, National Institutes of Health

Reinforcement Exercises: Space Walk

Astronaut Sunita L. Williams, Expedition 14 flight engineer, participates in the mission's third planned session of extravehicular activity (EVA) as construction resumes on the International Space Station. Astronaut Robert L. Curbeam, (out of frame), STS-116 mission specialist, also participated in the 7-hour, 31-minute spacewalk. Image Credit: "Sunita Williams astronaut spacewalk" by NASA, via Wikimedia Commons

[6]

We have a complication to mention: many materials have different emissivity at different frequency,which is the property of light that we perceive as colors. If the fraction electromagnetic radiation reflected by an object is the same at all visible frequencies, the object is gray; if the fraction depends on the frequency, the object has some other color. For instance, a red or reddish object reflects red light more strongly than other visible frequencies and because it absorbs less red, it

An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=2788

6. "Sunita Williams astronaut spacewalk" by NASA, via Wikimedia Commons is in the public domain

radiates less red when hot. Therefore its emissivity would be lower at frequencies we see as red. Differential reflection and absorption of frequencies outside the visible range have no effect on what we see, but they may have physically important effects with regard to thermal radiation. Skin is a very good absorber and emitter of infrared radiation, having an emissivity of 0.97 in the infrared. This high infrared emissivity is why we can so easily feel infrared radiation from a campfire on warming our skin, but also why our bodies readily lose thermal energy by infrared radiation. [7]OpenStax University Physics, University Physics Volume 2. OpenStax CNX. Nov 12, 2018 http://cnx.org/contents/7a0f9770-1c44-4acd-9920-1cd9a99f2a1e@14.10[/footnote]

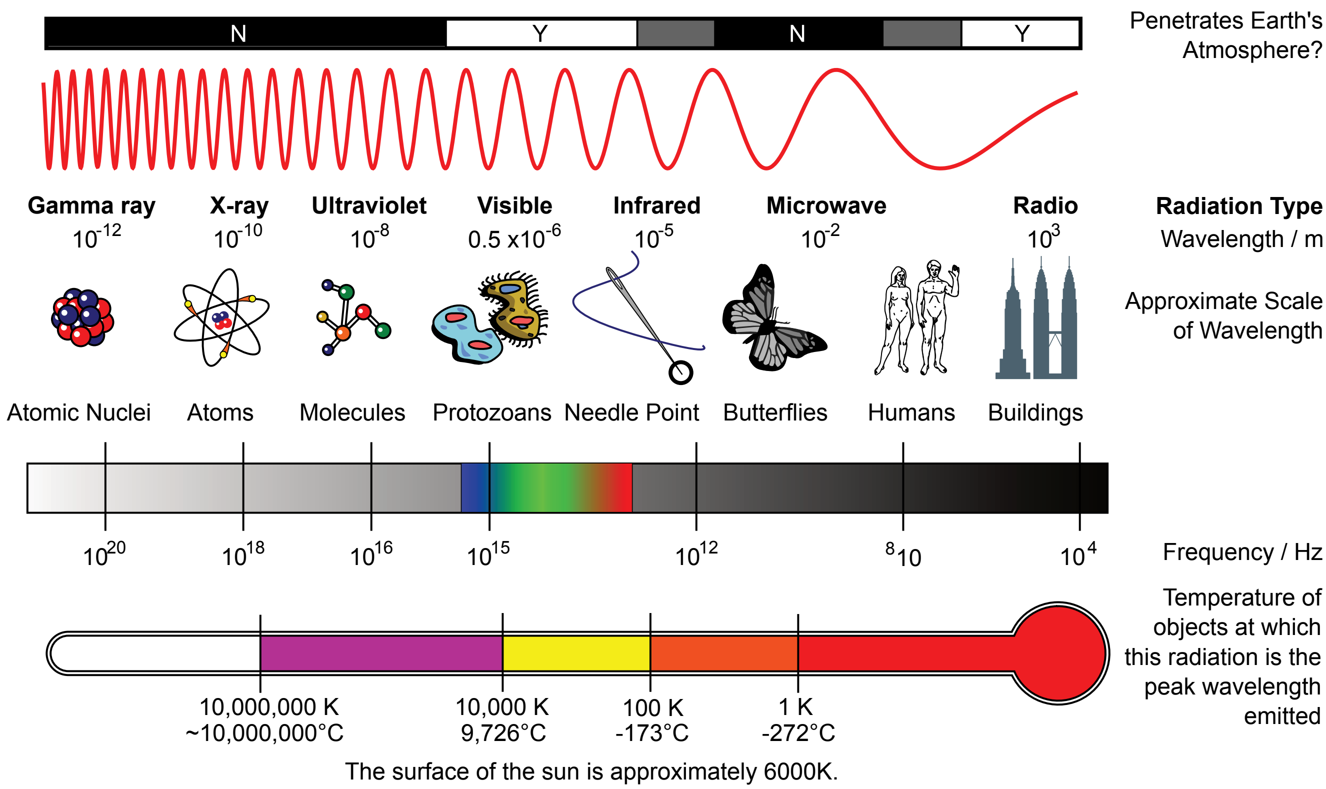
7.

CHAPTER 94.

THERMAL RADIATION SPECTRA

THE ELECTROMAGNETIC SPECTRUM

Different names are used for electromagnetic radiation (light waves) with various ranges of frequency: radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays. Collectively these ranges of frequencies make up the electromagnetic spectrum shown in the following diagram. The range frequencies that we can see is known as the visible spectrum, and we perceive the different frequencies within the visible spectrum as different colors. The wavelength of light, or any wave, is the distance between successive crests (peaks) of the wave. The frequency and wavelength of light waves are directly related and we can sometimes more easily relate to wavelength by comparing it to the length of familiar objects, so we often use wavelength instead of frequency to describe colors and the electromagnetic spectrum as a whole.



The electromagnetic spectrum. "EM Spectrum Properties reflected" by Inductiveload, via Wikimedia Commons

[1]

We can summarize the previous diagram in tabular form:

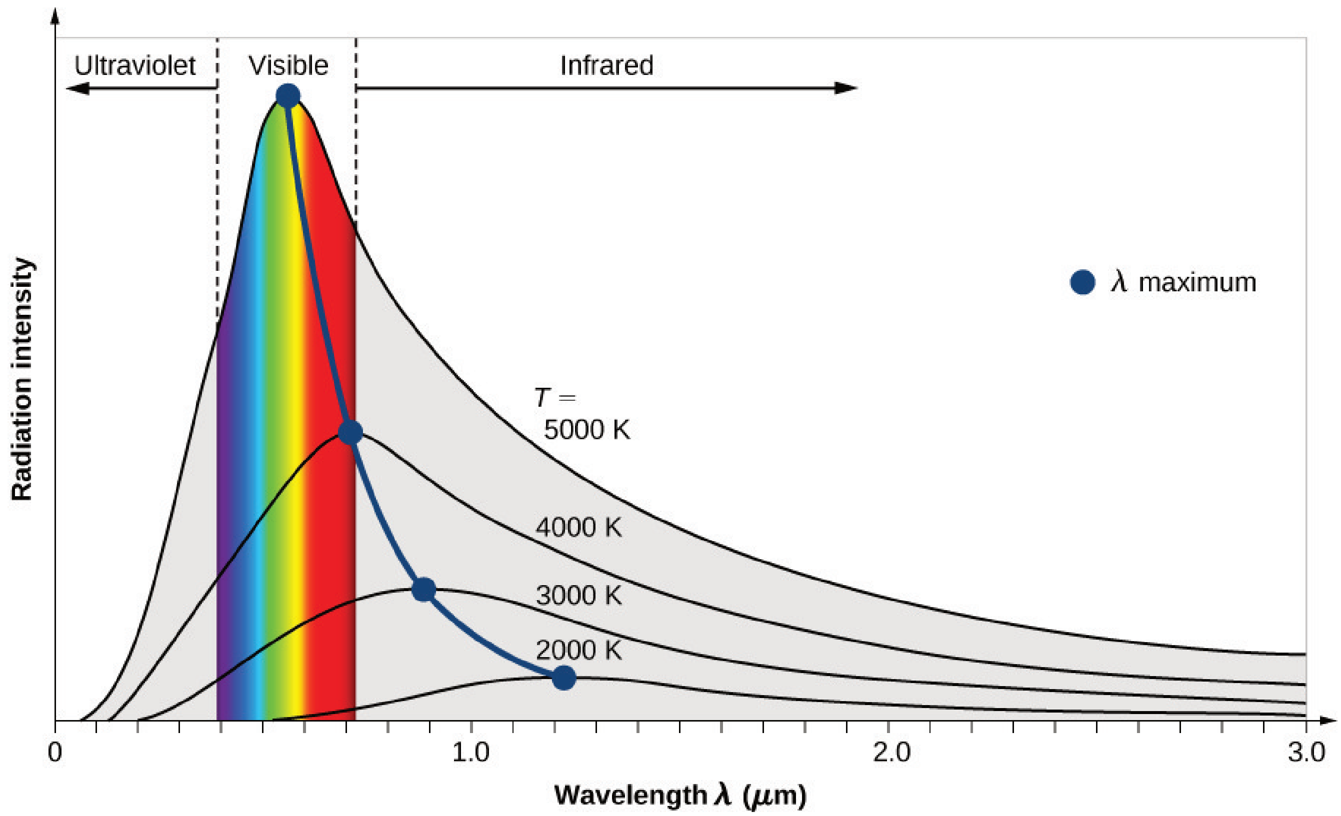
The previous diagram in tabular form

Radiation Type	Wavelength (**m**)	Approximate Wavelength Scale	Frequency (**Hz**)	Temperature of object with thermal radiation peak at this wavelength (**K**)	Significant penetration through atmosphere?
Gamma Ray	10^{-12}	Atomic Nucli	10^{20}		No
X-ray	10^{-10}	Atoms	10^{18}	10,000,000	No
Ultraviolet (UV)	10^{-8}	Molecules	10^{16}		No (more at longer wavelength)
Visible	0.5^{-6}	Protozoans	10^{15}	10,000	Yes
Infrared (IR)	10^{-5}	Needle Point	10^{12}	100	Yes (less at longer wavelength)
Microwave	10^{-2}	Butterflies	10^{8}	1	No
Radio	10^{3}	Humans to Buildings	10^{4}		Yes (less at shorter wavelength)

BLACK BODY RADIATION

A theoretically perfect emitter for which the emissivity is one ($epsilon = 1$) is known as black body emitter, because such an emitter would also be a perfect absorber and would thus appear completely black. The shape amount of light emitted at each wavelength defines the emission spectrum of the black body, which depends only on temperature in a well-defined way:

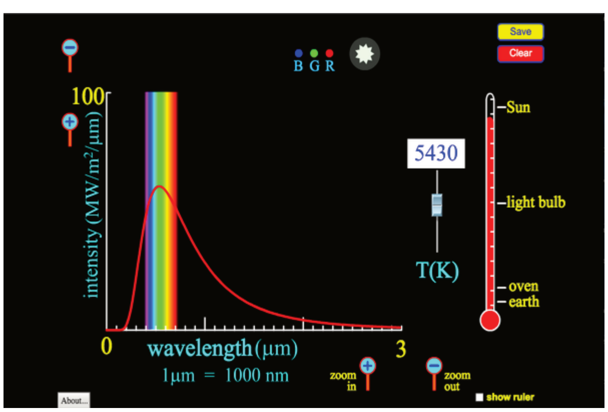
1. "EM Spectrum Properties reflected" by Inductiveload [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons



The intensity of black body radiation plotted against the wavelength of the emitted radiation. Each curve corresponds to a different black body temperature, starting with a low temperature (the lowest curve) to a high temperature (the highest curve). Image Credit: OpenStax University Physics Volume 3.

[2]

This simulations allows you to see how the black body emission spectrum depends on temperature:



2. OpenStax University Physics, University Physics Volume 3. OpenStax CNX. Nov 12, 2018 http://cnx.org/contents/af275420-6050-4707-995c-57b9cc13c358@10.14.

Exercises

We are often able to approximate the temperature of objects by assuming they are black body emitters and matching up their emission spectrum with that of a black body with a known temperature. This is the basic principle behind thermal imaging cameras and handheld infrared (IR) thermometers such as the one in the following image. (Note that IR thermometers are often include a low power laser to improve aim, but contrary to popular belief, the laser is not involved in the temperature measurement).

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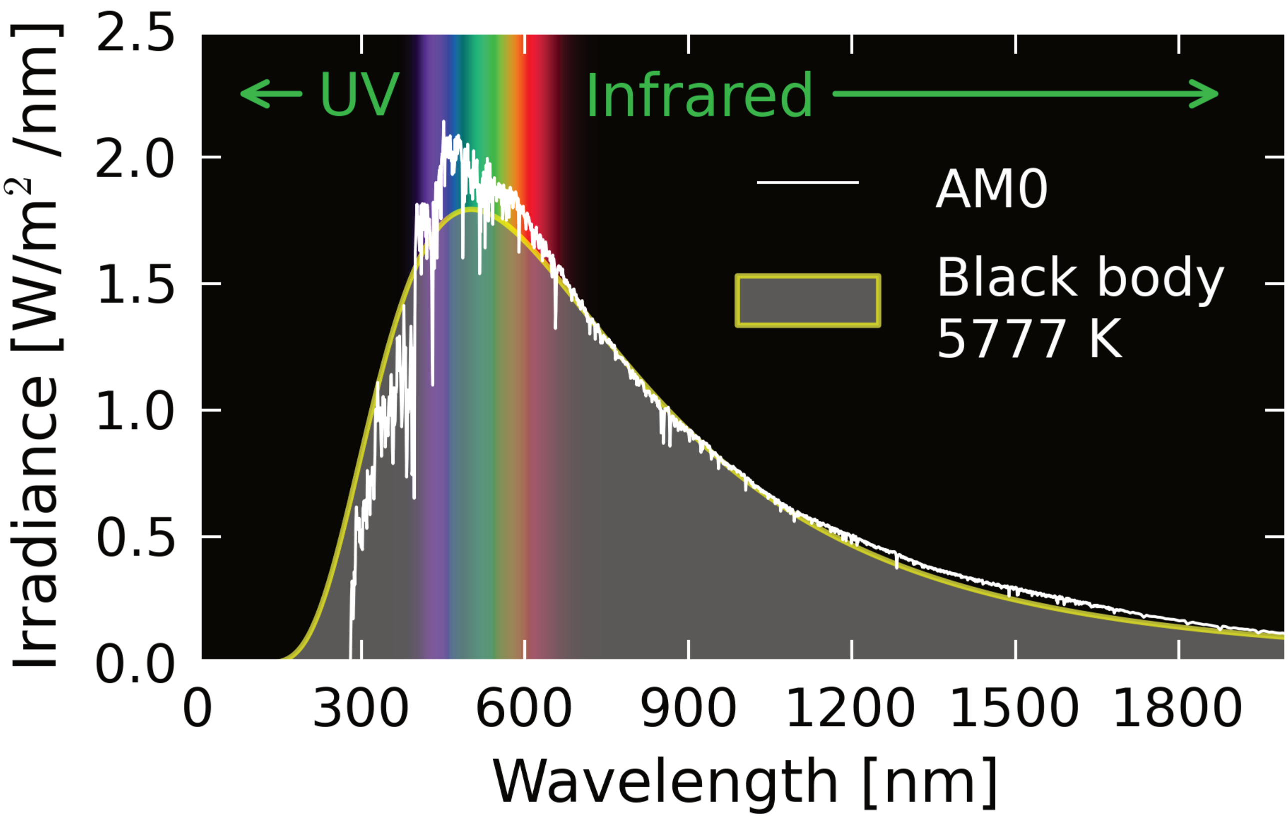
Contact tracers at a hospital in Conakry, Guinea demonstrate how to use a ThermoFlash infrared thermometer to monitor the temperatures of people who have come in contact with Ebola patients. Contacts are monitored for 21 days so that they can be isolated and treated as soon as possible if they develop symptoms. Image Credit: Infrared thermometer training by CDC Global via Wikimedia Commons.

[3]

For example, we can estimate the surface temperature of the sun to be roughly 6000 **K** (10,000 °**F**) because the actual emission spectrum of the Sun best matches the black body emission spectrum of an object at 6000 **K**, as seen in the following graph. Notice that the peak of the Sun's emission spectrum is in the visible range, but that significant radiation power is found in the UV and IR regions. The UV light is capable of penetrating the dead out layer of skin (epidermis) and breaking some molecular bonds in your cells, including those in DNA, which can lead to sunburn and increased risk of skin cancer.

3. Infrared thermometer training by CDC Global [CC BY 2.0 (https://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons



Emission spectrum of the sun as measured above the Earth's atmosphere (AM0) compared to the black body spectrum of an object at 5777 ***K****. Image Credit: Solar AM0 spectrum with visible spectrum background (en) by Danmichaelo [Public domain], from Wikimedia Commons*

Everyday Example: Incandescent vs LED and Fluorescent Light Bulbs

Incandescent light bulbs use thermal radiation to generate light. In order for their emission spectrum to contain significant visible light their temperature must be several thousand Kelvin, as seen from the previous graph showing black body emission spectra at several temperatures. Temperatures of 3000 **K** to 4000 **K** are achieved by running electric current through the narrow filaments of inside the bulbs to cause resistive heating (conversion of electric potential energy to thermal energy). The filaments are made of high temperature tolerant metals like tungsten to prevent melting. Additionally, the majority of air within the bulb has been removed to prevent conduction and natural convection from heating the glass and to prevent the filaments from quickly oxidizing (rusting). The emission spectra for objects at 3000 **K** to 4000 **K** show us that much of their radiated power is in the IR range rather than the visible range, and thus doesn't provide useful illumination. Consequently, much of the electrical energy used to power incandescent light bulbs goes to waste. In fact, glass does absorb IR radiation so much of the wasted energy simply goes into making the bulb glass hot, in some cases dangerously so. Fluorescent and LED bulbs don't use thermal radiation to generate light. Instead they apply voltages to energize electric charges trapped in atoms or in semi-conductor materials. When the electrons de-energize they emitted light at specific wavelengths, reducing the wasteful production of non-visible light. However, light from incandescent bulbs is sometimes considered more pleasing because it more closely resembles the emission spectrum of fire.

DANGEROUSLY HOT CARS

Some materials are transparent to visible light, but readily absorb IR light (notice how glasses prevent IR light from reaching the camera in this thermal image). Liquid water, water vapor, carbon dioxide (CO_2) gas and most types of glass behave this way. The emission spectrum of the sun shown above has significant emission in the UV, visible, and IR parts of the electromagnetic spectrum. The visible light gets through the glass, which is why the glass appears transparent to you. The majority of UV is absorbed or reflected, preventing you from getting sunburn inside the car. The glass absorbs much of the IR light, which is re-radiated in both directions, in and out of the car. The visible light that gets through is partially absorbed by the interior of the car (especially if the interior is dark). That absorbed visible light is then re-radiated as IR light because the interior of the car is not nearly hot to enough to radiate visible light like the sun. That re-radiated IR light is absorbed by the glass and re-radiated again in both directions, in and out of the car. Therefore a significant portion of the incoming visible light energy gets trapped inside the car and the interior temperature can rise quickly, even if the outside air temperature is cool. Green houses use this same phenomenon to keep plants warm in cool weather, so this phenomenon is commonly known as the green house effect. It's never a good idea to leave children or pets in cars. Even if you perform thoughtful calculations to predict the interior temperature for a given set of conditions such as air temperature, wind speed, and cloudiness, those conditions can change quickly. It's best not to risk injury to loved ones.

THE GREENHOUSE GAS EFFECT

The Earth's atmosphere acts like a car's windshield. The atmosphere lets most UV and visible light through, but significant IR light is absorbed, primarily by water vapor and carbon dioxide gas. With respect to the Earth, this green-house effect is known as the Green House Gas Effect because the phenomenon is caused by gasses in the atmosphere instead of glass or plastic.

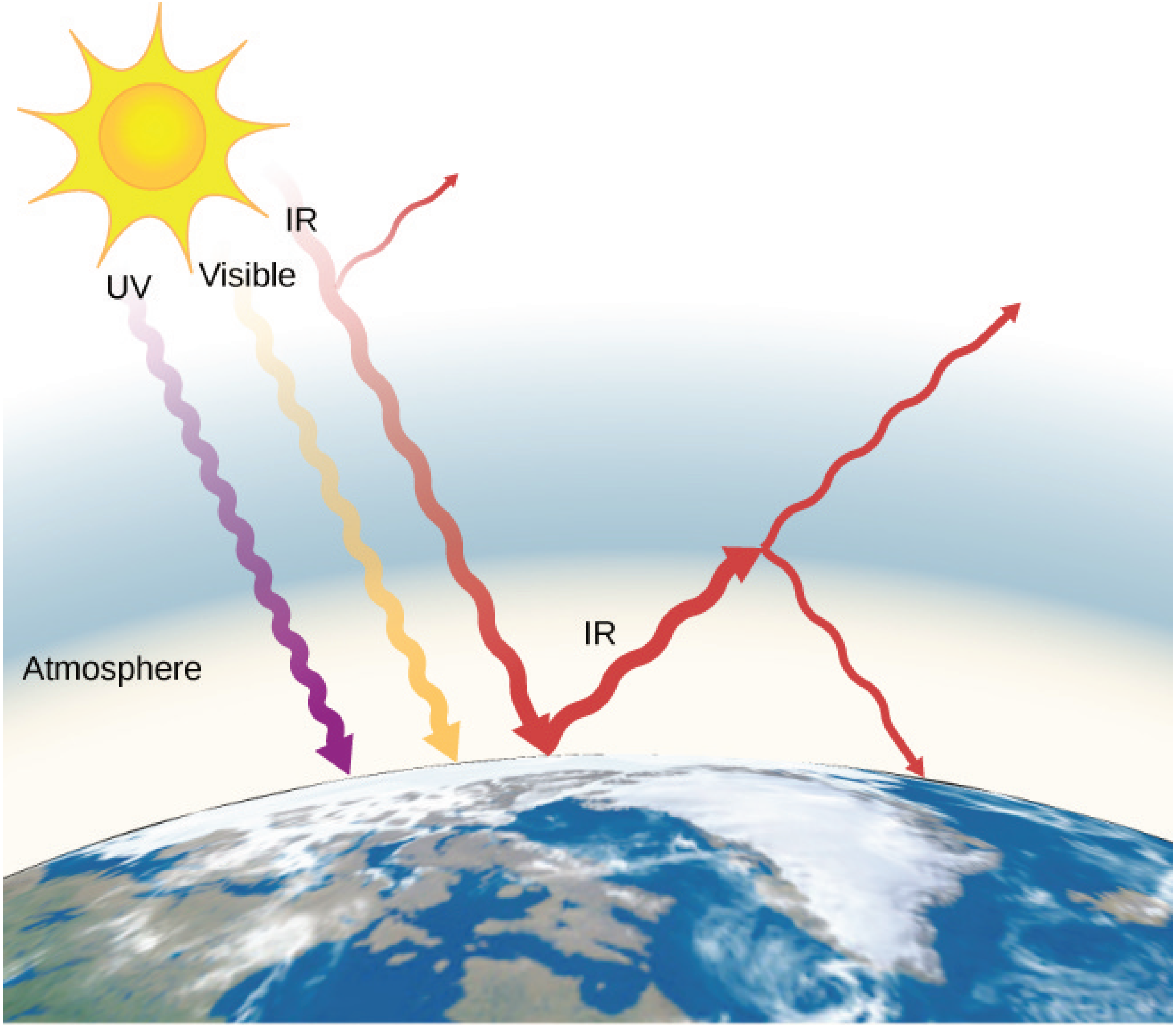


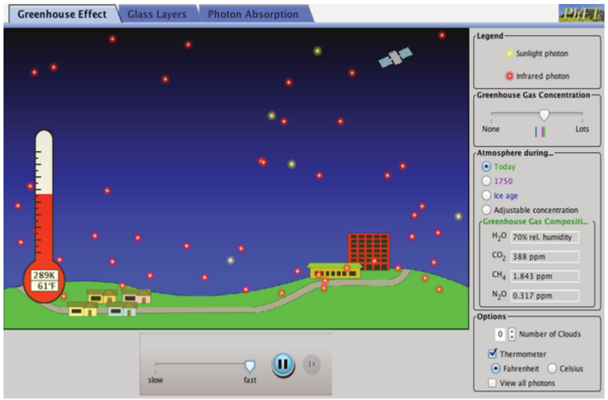
Illustration of the green house gas effect. UV, visible, and some IR light pass through the atmosphere. The UV and visible light are largely transformed to IR light. Only some of that IR light is able to escape back into space, the rest is trapped and the energy it contains increases the Earth's average temperature. Image Credit: OpenStax University Physics.

[4]

The green house gas effect helps to keep the Earth's temperature about 40 **°C** warmer than it would be without an atmosphere, which is a generally a good thing for us because most water on Earth would be frozen otherwise. Humans have established our modern infrastructure in accordance with the global climate that was present over the last few hundred years, but emission of carbon dioxide and methane (and other greenhouse gases) into Earth's atmosphere from human activities strengthens the green house gas effect and increases the average temperature of the Earth. Higher temperature means more thermal energy is available to drive more powerful convection cells and other thermodynamic processes that define weather and climate. The resulting changes in global

4. OpenStax University Physics, University Physics. OpenStax CNX. Oct 6, 2016 http://cnx.org/contents/74fd2873-157d-4392-bf01-2fccab830f2c@1.585

climate are likely to cause a variety of dangerous and expensive consequences such as higher storm intensity, rising sea levels, and increased flooding in certain areas with prolonged drought in others.[5][6] The following simulation allows you to examine how the green house gas effect works.



Click to Run

5. "Fourth National Climate Assessment" by U.S. Global Change Research Program
6. OpenStax University Physics, University Physics. OpenStax CNX. Oct 6, 2016 http://cnx.org/contents/74fd2873-157d-4392-bf01-2fccab830f2c@1.585

CHAPTER 95.

COLD WEATHER SURVIVAL TIME

Stages of Hypothermia

Stage	Core Body Temperature °C	Symptoms
Mild Hypothermia	35°-33°	shivering, poor judgment, amnesia and apathy, increased heart and respiratory rate, cold and/or pale skin
Moderate Hypothermia	32.9°-27°	progressively decreasing levels of consciousness, stupor, shivering stops, decreased heart and respiratory rate, decreased reflex and voluntary motion, paradoxical undressing.
Severe Hypothermia	< 26.9°	low blood pressure and bradycardia, no reflex, loss of consciousness, coma, death

[1]

Throughout this unit we have analyzed the rate of heat loss during a cold weather survival situation in which a person is wearing a single layer of thin clothing against an 10 **mph** wind and a -3 **°C** air temperature. Our analysis shows that collectively the person would experience a 200 **W** heat loss rate due to thermal radiation and a 1100 **W** heat loss rate due to forced convection. We also found that using a space blanket to reduce the wind chill and thermal radiation would leave only 160 **W** of heat loss rate rate due to conduction across the clothing. The typical person has a thermal power of 100 **W**, but shivering can increase that to 250 **W**.[2] It would be interesting to know, given these values for thermal power and heat loss rate, how quickly body temperature would actually change. In order to answer that question we need to learn about specific heat and heat capacity.

HUMAN HEAT CAPACITY

In the fight to maintain body temperature the human body gets assistance from the fact that the body is primarily made of water. The amount of thermal energy required to change the temperature of the body is relatively high compared to other objects of the same mass because water has a very high specific heat (*c*). Specific heat is a material property that defines the amount of thermal energy removed from one unit mass of the material when it's temperature changes by one unit of temperature. For example, water has a specific heat of 4186 **J**/(**kg C°**) so 4186 **J** of thermal energy must be removed from 1 **kg** of water in order for the temperature to drop by 1 **C°**. Multiplying the

1. Adapted from "Web-based hypothermia information: a critical assessment of Internet resources and a comparison to peer-reviewed literature" by M Spencer, Jeremy & Sheridan, Scott, Perspectives in public health, 135(2) · February 2014
2. "Nutritional Needs In Cold And In High-Altitude Environments: Applications for Military Personnel in Field Operations" byAndrew J. Young, Michael N. Sawka and Kent B. Pandolf, National Center for Biotechnology Information, National Institutes of Health

specific heat of a material by the mass of the material gives the heat capacity (*C*) of the object. For example, the heat capacity for 80 **kg** of water would be: 4186 **J**/(**kg C°**) x 80 **kg** = 334,880 **J**/(**C°**), meaning that 334,880 **J** must be removed to drop the temperature of 80 **kg** of water by 1 C°.

Reinforcement Exercises

Now that we know how to calculate heat capacity we are ready to calculate the amount of energy required to change the temperature of the body by a dangerous amount. We just multiply the mass (*m*) by the specific heat (*c*) to get heat capacity, which we then we multiply by a dangerous temperature change ($DeltaT = T_f - T_i$) to get the heat required (*Q*). This entire process can be summed up by the equation:

(1) $Q = mc\Delta T$

Notice that if the temperature is dropping then final temperature is less than the initial temperature so $DeltaT$ will be negative, which makes heat negative, indicating that thermal energy is leaving the object. The equation works for heating as well as cooling because in that case $DeltaT$ and Q will be positive indicating that thermal energy is entering the material.

Reinforcement Exercises

The following chart provides specific heat values for various substances. Notice the relatively high specific heat of water.

Table of Specific Heat Values

substances	**specific heat (*c*)**	
Solids	**J/kg·°C**	**kcal/kg·°C**
Aluminum	900	0.215

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substances	specific heat (*c*)	
Asbestos	800	0.19
Concrete, granite (average)	840	0.20
Copper	387	0.0924
Glass	840	0.20
Gold	129	0.0308
Human body (average at 37 °C)	3500	0.83
Ice (average, -50°C to 0°C)	2090	0.50
Iron, steel	452	0.108
Lead	128	0.0305
Silver	235	0.0562
Wood	1700	0.4
Liquids		
Benzene	1740	0.415
Ethanol	2450	0.586
Glycerin	2410	0.576
Mercury	139	0.0333
Water (15.0 °C)	4186	1.000
Gases		
Air (dry)	721 (1015)	0.172 (0.242)
Ammonia	1670 (2190)	0.399 (0.523)
Carbon dioxide	638 (833)	0.152 (0.199)
Nitrogen	739 (1040)	0.177 (0.248)
Oxygen	651 (913)	0.156 (0.218)
Steam (100°C)	1520 (2020)	0.363 (0.482)

3

Everyday Examples: Cold Weather Survival Time

Applying the previous equation to the human body we can estimate how long it would take body temperature to drop from a normal 37 **°C** down to the edge of moderate hypothermia at 33 **°C** in the example survival situations discuss so far in this unit. Let's use relatively common human mass of about 80 **kg** and the average specific heat of human tissue of 3470 **J**/(**kg C°**). [4]First we find the heat loss required for the temperature drop:

$$Q = mc\Delta T = (80\,\mathbf{kg})\left(3470\,\frac{\mathbf{J}}{\mathbf{kg\,C^{\circ}}}\right)(33\ \mathbf{C}^{\circ} - 37\ \mathbf{C}^{\circ}) \approx 1,000,000\,\mathbf{J}$$

We know that in our example of a 10 **mph** wind and a -3 **°C** air temperature we found that a person with thin clothing and no space blanket experienced 1100 **W** of convective heat loss and 200 **W** of radiative heat loss for a total of 1300 **W**. If the

3. OpenStax, College Physics. OpenStax CNX. Nov 8, 2018 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@14.4
4. Engineering ToolBox, (2001). [online] Available at: https://www.engineeringtoolbox.com [Accessed 27 1 2019]

person was shivering then their thermal power would be roughly 250 **W**. This person would have a 1150 **W** thermal power deficit, which means they lose 1150 Joules of thermal energy each second. Dividing the dangerous heat loss we calculated above by the thermal power deficit gives us the time required to lose that much heat:

$$t = \frac{1,000,000\,\mathbf{J}}{1150\,\mathbf{J/s}} \approx 900\,\mathbf{s}$$

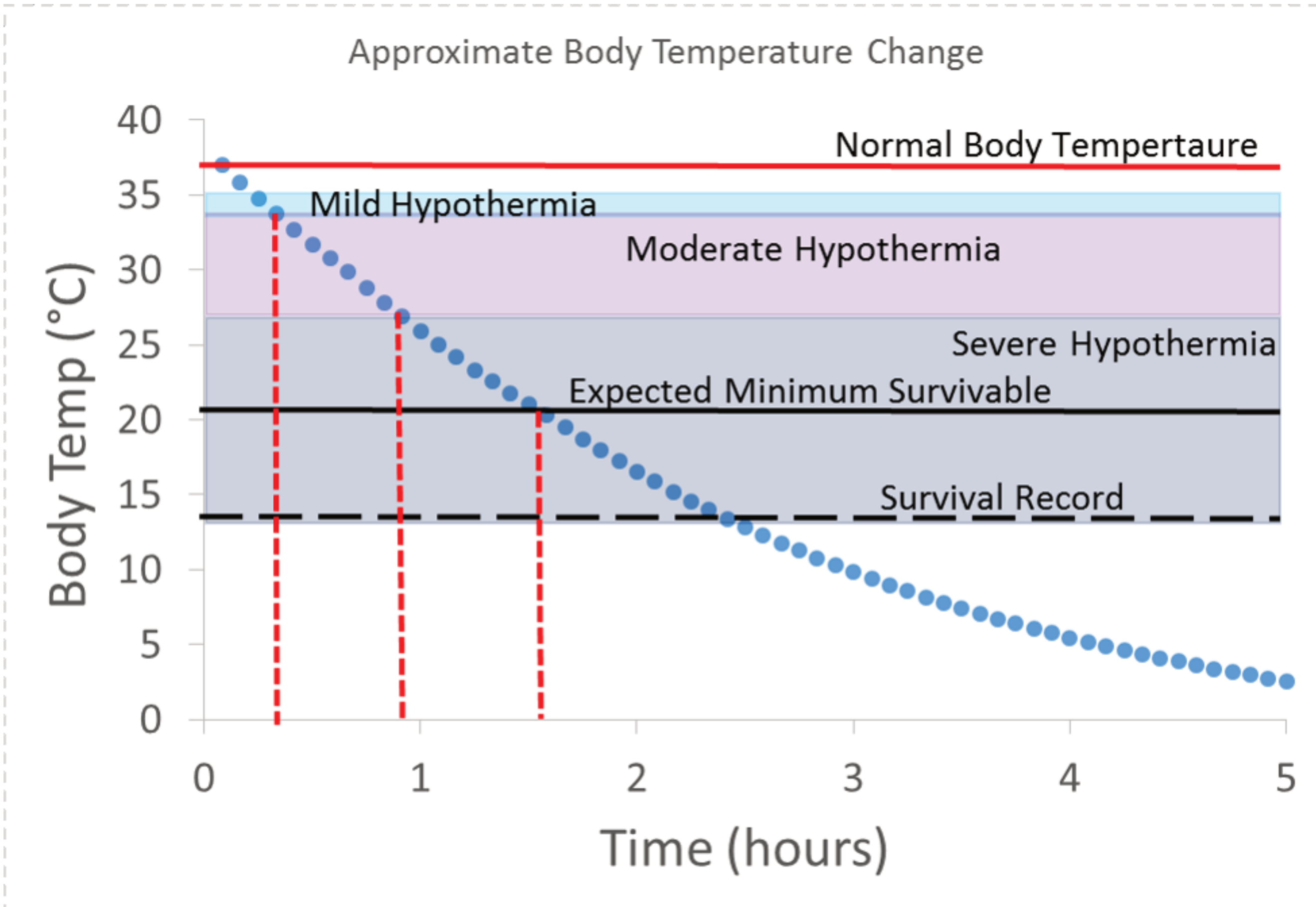
Dividing the 900 **s** by 60 (**s/min**), we see that hypothermia would be reached in only 14 minutes. In reality, the rate of heat loss depends on the temperature difference so the rate of heat loss would not be constant, but instead it would slow a just bit as body temperature decreased. In our example case the 40.9 **C°** difference between the body temperature and environment temperature changed by only about 3 **C°** (seven percent). Ignoring this effect gives a reasonable approximation for the time until moderate hypothermia. The next two sections will address this approximation and allow us to calculate the time required for more significant temperature changes.

RATES OF BODY TEMPERATURE CHANGE

The rate at which thermal energy is transferred out of the body depends on the difference in temperature between the body and the environment. As the body cools closer to the environmental temperature the rate will decrease. In the previous example we ignored this reality and assumed that the cooling rate was constant, which was reasonable because we only examined a very small temperature change. For our example situation we found that mild hypothermia would be reached in only twenty minutes. The graph below was produced by calculating the body temperature while accounting for a cooling rate that depends on the temperature difference. This was done using a numerical model:

1. calculating a heat transfer rate for the initial body temperature due to both thermal radiation and forced convection
2. using that heat transfer rate to calculate the amount of heat transferred over a relatively short time interval
3. using the amount of heat transferred to calculate a resulting reduction in body temperature
4. calculating a new body temperature by subtracting the reduction in body temperature
5. repeat 1-5 until temperature was well beyond survival temperature, keeping track of the temperatures and times to make the graph

We see that the time to mild hypothermia is actually more like 30 mins. We also see that severe hypothermia could set in after less than an hour and the minimum survivable temperature could be reached in under two hours. For the purpose of these calculations we assumed a thermal power of 250 **W** while shivering, and that shivering stops when the body reaches 30 °**C**, at which point thermal power returns to 100 **W**. We also assumed the that thermal power dropped to zero when body temperature reached 21 °**C**.



Predicted body temperature during a simplified example survival situation.

Approximate body temperature vs. time for an 80 **kg** person in 25 °**F** air temperature and 10 mph wind (-3 °**C** , 4.5 **m/s**). For the purpose of these calculations we assumed a thermal power of 250 **W** while shivering, that shivering stops at 30 °**C** at which point thermal power returns to 100 **W**, and that thermal power dropped to zero below 21 °**C**. Minimum survivable body temperature and record low body temperature survived were found at "How Cold Can a Body Get" by Ali Venosa, Medical Daily and "Frozen Alive" by Peter Stark, Outside Magazine.

Modeling how body temperature changes with time under different insulation and temperature conditions allows forensic investigators to measure a body's temperature and work backwards to determine the time at which body temperature started to drop from normal. In this way time of death can be determined (unless of course the person was hypothermic or hyperthermic before death).

CHAPTER 96.

PREVENTING HYPERTHERMIA

Whole body hyperthermia is a method to raise a patient's body temperature for the treatment of advanced cancer. This technique is based on laboratory studies that show cancer cells are more sensitive to heat injury than normal cells. Physicians induce hyperthermia using a high-flow water suit controlled by a microprocessor, a machine which closely monitors body temperature. The patient's body temperature is raised by the insulated build-up of metabolic (body) heat, plus by the heat delivered by the warm-water suit. Image Credit: Hyperthermia Patient by Mike Mitchell (photographer) [Public domain], via Wikimedia Commons

[1]

Hyperthermia, as opposed to hypothermia, occurs when body temperature increases as thermal energy builds up the body because heat is not transferred out of the body fast enough to keep up with the body's thermal power. We can try to avoid such a situation by minimizing our work output to reduce overall thermal power (remember, the body has low efficiency so doing work means generating thermal energy). We can also use our understanding of the conduction, convection, and thermal radiation to ensure maximum heat transfer away from the body. For example, we can minimize the thickness of clothing to increase conduction, wear light colored clothing to reduce radiation absorbed from the sun, and encourage air circulation (convection).

1. Hyperthermia Patient by Mike Mitchell (photographer) [Public domain], via Wikimedia Commons

The clothing warn by the people in this image was designed to minimize energy absorbed from the sun (light colors), not hinder conduction (thin), and allow convection (open, breathable). Image credit: OpenStax University Physics.

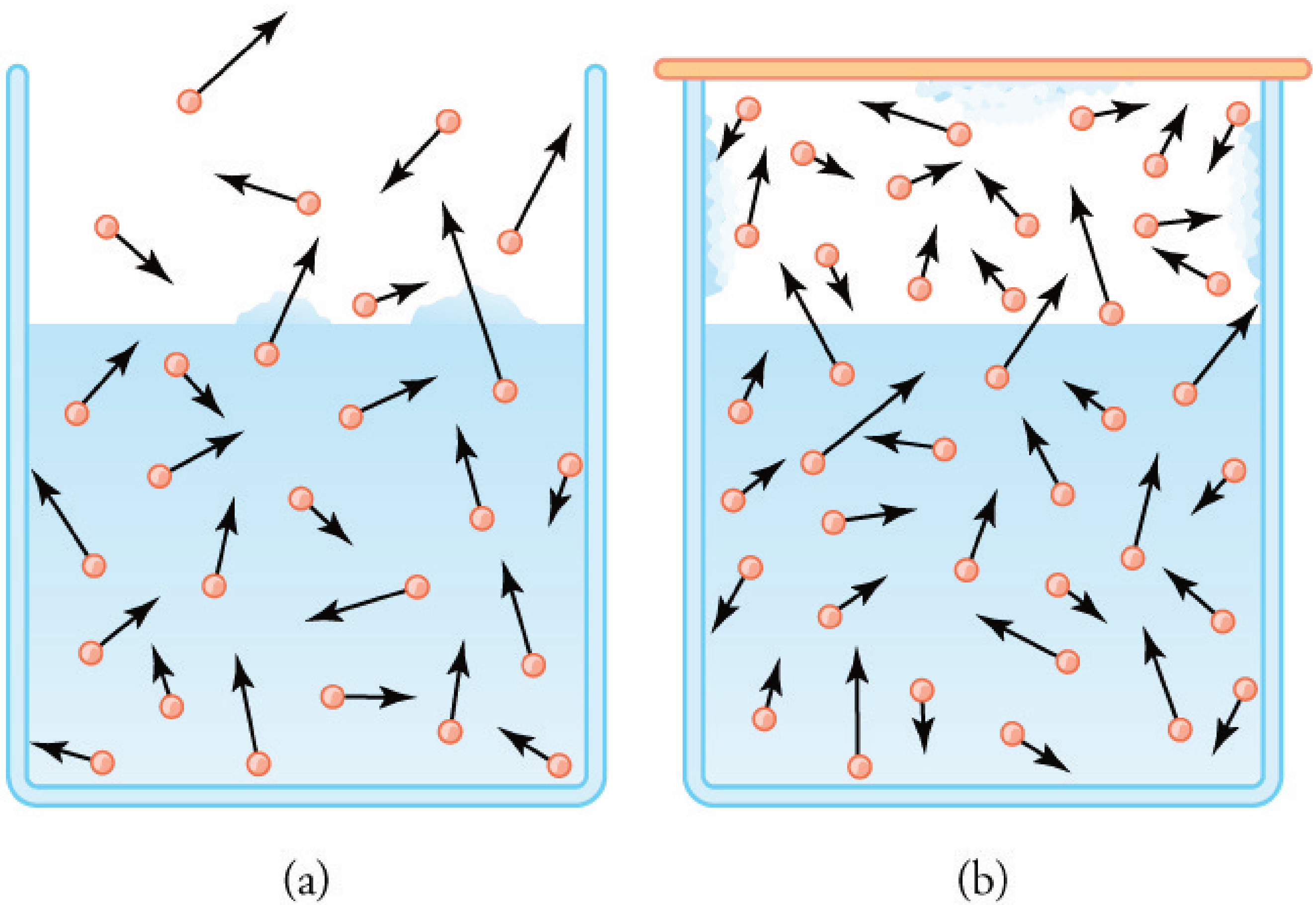
[2]

SWEATING

In some cases our thermal power outpaces the rate at which we exhaust heat by conduction, convection and radiation. Our strategy to deal with this situation is sweating. When we sweat some of the water on our skin evaporates into a water vapor. Only the molecules with the most kinetic energy are able to escape the attraction of their fellow water molecules and enter the air. Therefore the evaporating molecules remove more than a fair share of the thermal energy (thermal energy is just molecular kinetic energy remember). The remaining liquid water molecules then have less thermal energy on average, so they are at a lower temperature and must absorb more energy from

2. OpenStax University Physics, University Physics Volume 2. OpenStax CNX. Feb 6, 2019 http://cnx.org/contents/7a0f9770-1c44-4acd-9920-1cd9a99f2a1e@15.2

your body as they come to thermal equilibrium with your body again. This evaporation process allows the body to dump thermal energy even when the environment is too warm for significant heat loss by conduction, convection, and radiation. The amount of energy removed by evaporation is quantified by the latent heat of vaporization (L_v). For water L_v = 2,260 **kJ/kg**, which means that for every kilogram of sweat evaporated, 2260 kiloJoules of energy is transferred away from the skin.



The liquid temperature is determined by the average of the kinetic energy of atoms and molecules. At any moment the molecules will have a range of individual kinetic energies, some will have greater energy than the average and some less. (a) Those molecules with sufficiently large kinetic energy can break away to the vapor phase even at temperatures below the ordinary boiling point. (b) If the container is sealed, evaporation will continue until the space above the water reaches 100% Relative Humidity, meaning there is so many water molecules in the vapor phase that they re-enter the liquid phase just as often as they evaporate. At 100% humidity evaporation will no longer provide a net cooling effect. Image Credit: OpenStax, Humidity, Evaporation, and Boiling

3

3. OpenStax, Humidity, Evaporation, and Boiling. OpenStax CNX. Sep 9, 2013 http://cnx.org/contents/030347e9-f128-486f-a779-019ac474ff90@5

Everyday Example

A person working in an environment that happens to be very close to body temperature (about 100 **°F**) would not be able to get rid of thermal energy by conduction, convection, or radiation. If the person was working hard and generating about 250 W of thermal power (similar to the thermal power while shivering) then how much sweat would need to be evaporated each hour to keep their body temperature from rising?

In order to keep the body temperature from rising the person needs to get rid of 250 **W** of thermal energy, that's 250 **J/s**. Let's convert that to Joules per hour:

(1) $$(250\,\mathbf{J/s}) = (250\,\mathbf{J/s})(60\,\mathbf{s/min})(60\,\mathbf{min/hr}) = 900,000\,\mathbf{J/hr}$$

Each kilogram of water that evaporates removes 2,260,000 **J** of energy, so only a fraction of a kilogram will need to be evaporated every hour:

(2) $$\frac{mass}{second} = \frac{900,000\,\mathbf{J/hr}}{2,260,000\,\mathbf{J/kg}} = 0.4\,\mathbf{kg/hr}$$

The body would need to evaporate 0.4 **kg** per hour. Water has a density of about 1 kg/L, so that would be a volume of 0.4 **L/hr**, or roughly 1.7 **cups/hr**, or 13.5 **fluid oz/hr**.

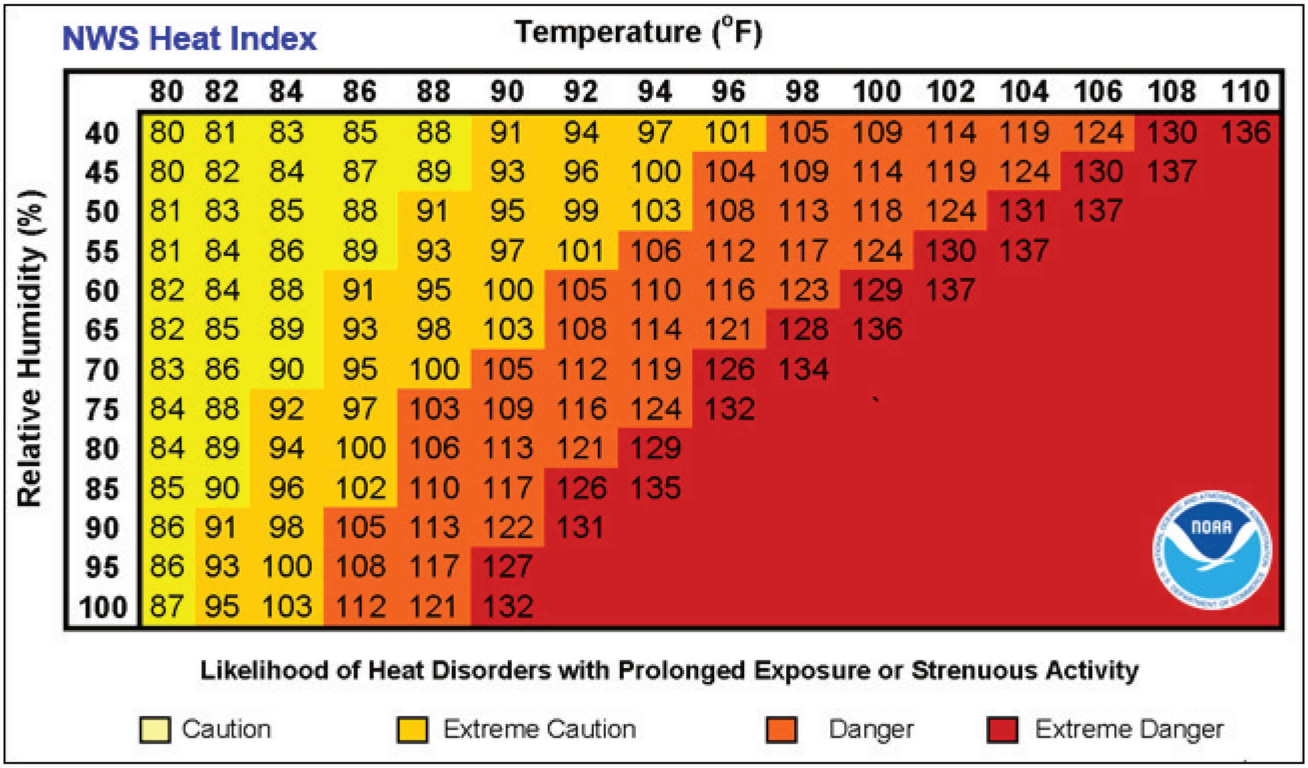
Exercises

[4]

An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=1083

4. "Zion National Park Visitor Center" by National Renewable Energy Laboratory, U.S. Department of Energy is in the Public Domain

HEAT INDEX



RH (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

The Heat Index is a measure of how hot it really feels when relative humidity is factored in with the actual air temperature. To find the Heat Index temperature, look at the Heat Index Chart above or check our Heat Index Calculator. As an example, if the air temperature is 96°F and the relative humidity is 65%, the heat index–how hot it feels–is 121°F. The red area without numbers indicates extreme danger. Image Credit: "Heat Index" by National Weather Service, NOAA is in the Public Domain

[5]

The rate at which water will evaporate depends on the liquid temperature and the relative humidity of the surrounding air. The relative humidity compares how many water molecules are in the vapor phase relative to the maximum number that could possibly be in the vapor phase at the current temperature. A relative humidity of 100% means that no more water molecules can be added to the vapor phase. If the humidity is high, then evaporation will be slow and may not provide sufficient cooling. The heat index takes into account both air temperature and the relative humidity to determine how difficult it will be for your body to exhaust heat. Specifically, the heat index provides the theoretical air temperature that would be required at 20% humidity to create the same difficulty in exhausting heat as the actual temperature and humidity. Heat index values were devised for shady conditions with a light wind. Exposure to full sun or stagnant air can increase feel-like values by up to 15 degrees!

5. "Heat Index" by National Weather Service, NOAA is in the Public Domain

Exercises

Everyday Examples: Winter Dry Skin

The Pacific Northwest is famous for its winter rain, fog and general high humidity. However, people in the pacific northwest often suffer from dry skin in winter, but not summer when humidity is often less than 20 **%**. . During winter, humid air is brought in from the outside and warmed by the heating system. That air still contains the same amount of water vapor, but is now at higher temperature, so the relative humidity is significantly reduced, even to the point of causing dry skin.

BOILING AND THE BENDS

We have learned that evaporation takes place even when a liquid isn't boiling, so we may be wondering what causes boiling and how is it different from normal evaporation? Water ordinarily contains significant amounts of dissolved air and other impurities, which are observed as small bubbles of air in a glass of water. The bubbles formed within the water so the relative humidity inside the bubbles is 100%, meaning the maximum possible number of water molecules are inside the bubble as vapor. Those molecules collide with the walls of the bubble causing an outward pressure. The speed of the water molecules increases with temperature, so the pressure they exert does as well. At 100 **°C** the internal pressure exerted by the water vapor is equal to the atmospheric pressure trying to collapse the bubbles, so rather than collapse they will expand and rise, causing boiling. Once water is boiling, any additional thermal energy input goes into changing liquid water to water vapor, so the water will not increase temperature. Turning up the burner on the stove will not cook the food faster, it will just more quickly boil away (evaporate) the water.

Everyday Examples: The Bends

At high altitude the atmospheric pressure is lower, so molecules of water vapor don't need to create as much pressure within bubbles to maintain boiling. Therefore, boiling will occur at a lower temperature and cooking foods by boiling will take longer. (Food packaging often gives alternative cook times for high altitude).

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The same process is responsible for *the bends*, which refers to the formation of nitrogen bubbles within the blood upon rapid ascent while SCUBA diving. You might imaging that you could hang out underwater by breathing through a hose, and that would work in very shallow water. However, the high pressure exerted by water at depths below roughly 2 **m** (6 **ft**) would prevent the diaphragm and rib cage from expanding to pull air into the lungs. At greater depths you need to breath from a pressurized container which helps to force air into your lungs against the additional hydrostatic pressure. Of course if you breathed from the container at shallow depth then the pressure would be too high and would cause damage to your lungs. A pressure regulator that outputs the appropriate pressure according to the water depth is the core of the SCUBA system.

There is always some gas dissolved in your blood, including carbon dioxide, oxygen, and nitrogen. The amount of dissolved gas is determined by the temperature and the pressure. If temperature is high enough, and pressure is low enough, then boiling will occur. Breathing high pressure air from a SCUBA system while at depth forces these gases to dissolve into your blood in the amounts determined by your body temperature and the high pressure.

When ascending, the pressure drops quickly, but the body temperature stays constant, so the blood gases can begin to boil, starting with Nitrogen. There is not issue with blood temperature here, blood is still at body temperature, but the bubbles are a problem for the cardiovascular system. To prevent *the bends*, you must ascend slowly, allowing the gasses to slowly escape from the blood and be expelled in the breath, without forming large bubbles in the blood.

To treat the bends a patient is placed in a hyperbaric (high pressure) chamber. The high pressure collapses the bubbles and prevents new ones from forming. The pressure is then slowly decreases to allow the blood gasses to escape slowly, simulating a gradual ascent.

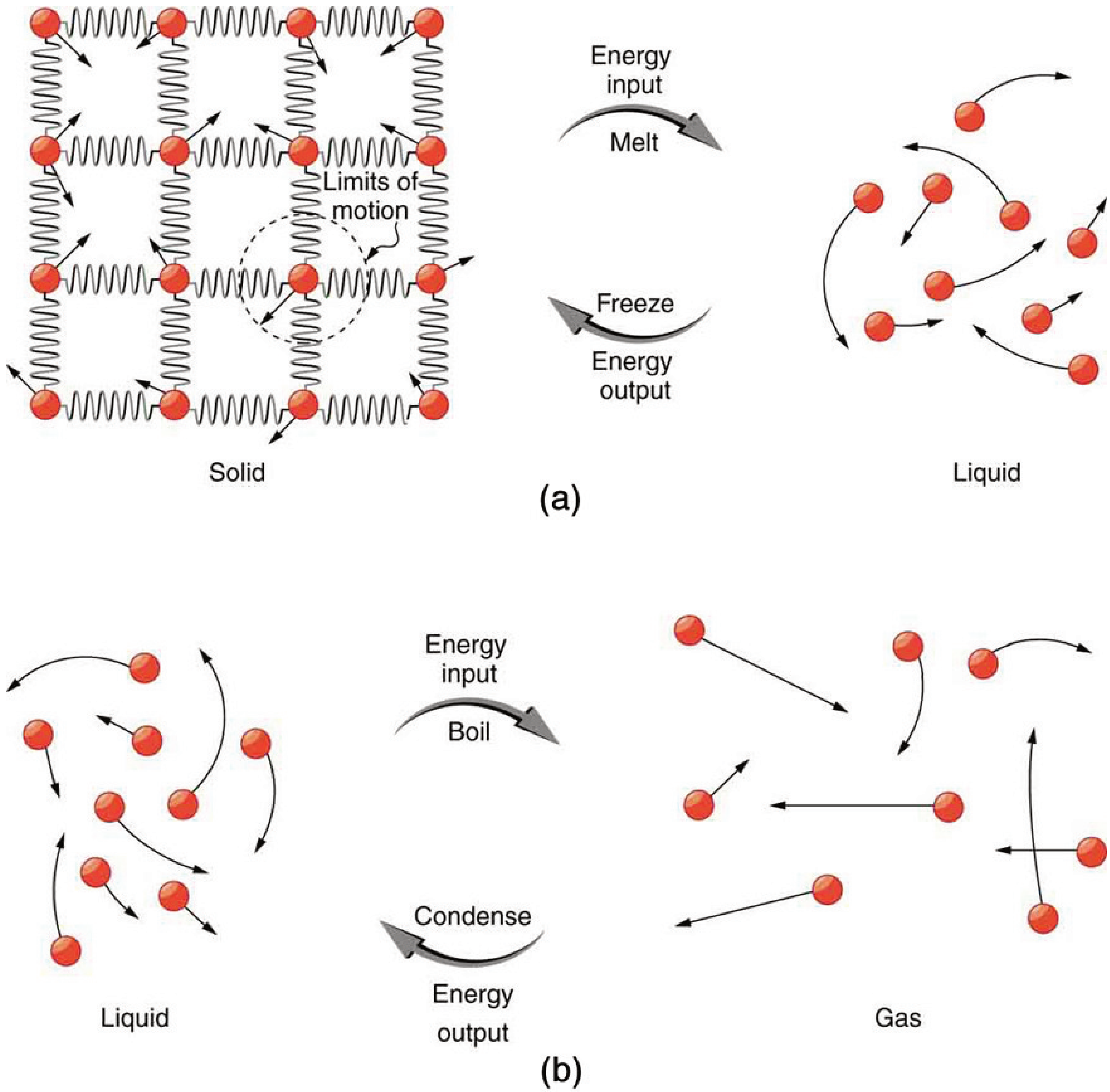
Students at the Naval Diving and Salvage Training Center undergo various training scenarios to prepare them for duties involving underwater emergencies and procedures. Image Credit: "Decompression Chamber" by U.S. Navy Mass Communication Specialist 2nd Class Jayme Pastoric, via Wikimedia Commons.

[6]

LATENT HEATS

We have learned that evaporation of liquid molecules removes thermal energy from the liquid. An exchange of thermal energy will accompany any such change of phase. The reverse process of condensation, in which vapor molecules stick together to form a liquid, will bring thermal energy into the liquid. The latent heat of vaporization also quantifies the energy exchanged during condensation.

6. "Decompression Chamber" by U.S. Navy Mass Communication Specialist 2nd Class Jayme Pastoric, is in the Public Domain.



Energy is required to partially overcome the attractive forces between molecules in a solid to form a liquid. That same energy must be removed for freezing to take place. (b) Molecules are separated by large distances when going from liquid to vapor, requiring significant energy to overcome molecular attraction. The same energy must be removed for condensation to take place. When causing a phase change by adding or removing thermal energy, there is no temperature change until the phase change is complete. Image Credit: OpenStax CNX

Changing from solid to liquid, known as melting, requires energy just as evaporation does. The thermal energy required to melt a solid will be pulled from the surrounding environment, thus lowering the environment temperature. In similar fashion to vaporization, the amount of energy removed by melting is quantified by a latent heat, in this case the latent heat of fusion (L_f). For water, L_f = 334 **kJ/kg**, which means that for every kilogram of ice melted, 334 kiloJoules of energy input is needed. Freezing releases the same amount of energy into the environment that melting requires as input. The temperature at which melting occurs (within a given pressure) is known as the melting point. The melting and boiling points and latent heats of various substances at standard atmospheric pressure are shown in the following chart:

Melting and Boiling points, and Latent Heats at Standard Atmospheric Pressure[7][/footnote]

		l_f			l_v	
Substance	**Melting point (°C)**	**kJ/kg**	**kcal/kg**	**Boiling point (°C)**	**kJ/kg**	**kcal/kg**
Helium	−269.7	5.23	1.25	−268.9	20.9	4.99
Hydrogen	−259.3	58.6	14.0	−252.9	452	108
Nitrogen	−210.0	25.5	6.09	−195.8	201	48.0
Oxygen	−218.8	13.8	3.30	−183.0	213	50.9
Ethanol	−114	104	24.9	78.3	854	204
Ammonia	−75		108	−33.4	1370	327
Mercury	−38.9	11.8	2.82	357	272	65.0
Water	0.00	334	79.8	100.0	2256[5]	539[6]
Sulfur	119	38.1	9.10	444.6	326	77.9
Lead	327	24.5	5.85	1750	871	208
Antimony	631	165	39.4	1440	561	134
Aluminum	660	380	90	2450	11400	2720
Silver	961	88.3	21.1	2193	2336	558
Gold	1063	64.5	15.4	2660	1578	377
Copper	1083	134	32.0	2595	5069	1211
Uranium	1133	84	20	3900	1900	454
Tungsten	3410	184	44	5900	4810	1150

Reinforcement Exercises

Everyday Examples: Melting Ice for Drinking Water

Spending more than a day in frozen landscapes (high altitude, high latitude, or both), will require melting ice/snow to make drinking water. Let's determine the thermal energy required to melt 10 **kg** of ice that started at 0 **°C**.

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7. [footnote]OpenStax CNX. Feb 27, 2019 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@14.44.

First we look up the latent heat of fusion for water in the previous chart and find L_f = 334 **kJ/kg**, or 334,000 **J/kg**. Using this value in the latent heat formula:

$$Q = mL_f = (10\,\mathbf{kg})(334,000\,\frac{\mathbf{J}}{\mathbf{kg}}) = 3,340,000\,\mathbf{J}$$

Now that we are familiar with the idea of latent heat, let's combine that with our understanding of the energy required to change temperature, to get a full approximation of the minimum amount of stove fuel required for a three-person, round-trip expedition to the summit of Denali, North America's highest mountain, at 20,380 **ft** (6495 **m**). Allowing for gradual acclimatization to altitude will reduce the likelihood of acquiring high altitude pulmonary edema and/or high altitude cerebral edema, so we will plan 21 days on the mountain.

First, let's figure out how much water we need. The combination of acclimatization and climbing effort will require at least 4 liters of water per person per day. The total volume we need is then:

$$V = (21 days)(3 people)(4\,\frac{\mathbf{L}}{day \cdot person}) = 252\,\mathbf{L}$$

The density of water is 1 **kg/L** so we will also need 252 **kg** of water. To get that mass of water we will need to warm and melt that mass of snow each day. The average temperature on the mountain will be -20 **°C** and we will assume the snow to be melted starts off at this temperature. Let's find the energy required to warm that mass of -20 **°C** snow up to 0 **°C**. We use a chart of specific heats to find c_{ice} = 2 **kJ/kg** = 2,000 **J/kg**. Using that value in our equation relating heat and temperature change:

$$Q = mc\Delta T = (252\,\mathbf{kg})(2,000\,\frac{\mathbf{J}}{\mathbf{kg\,C^\circ}})(20\,\frac{\mathbf{C^\circ}}{)} = 10,080,000\,\mathbf{J}$$

Next we need the energy to melt the snow:

$$Q = mL_f = (252\,\mathbf{kg})(334,000\,\frac{\mathbf{J}}{\mathbf{kg}}) = 8,4168,000\,\mathbf{J}$$

So far we need 10,080,000 **J** + 8,4168,000 **J** = 94,248,000 **J** to get ourselves enough water at 0 °C.

Typically the snow is brought to a boil to prevent sickness due to contamination by previous expeditions, and because a hot drink is great for mind and body after hauling a heavy pack and sled through deep snow for 12 hours in sub-zero temperatures at high altitude.

At altitude, the water will boil before reaching 100 **°C**. According to boiling point vs. altitude graph the boiling point of water at a mountain height of 13,000 **ft** will be about 190 **°F** (88 **°C**) rather than 212 **°F** (100**°C**). We will only need to raise the water temperature from 0 **°C** to 88 **°C** to achieve boiling. Water has a specific heat of 4186 **J/(kg C°)**, so we have:

$$Q = mc\Delta T = (252\,\mathbf{kg})(4186\,\frac{\mathbf{J}}{\mathbf{kg\,C^\circ}})(88\,\frac{\mathbf{C^\circ}}{)} = 92,828,736\,\mathbf{J}$$

All told, we need that 92,828,736 **J** plus our previous 94,248,000 **J** for a total of 187,076,736 **J**.

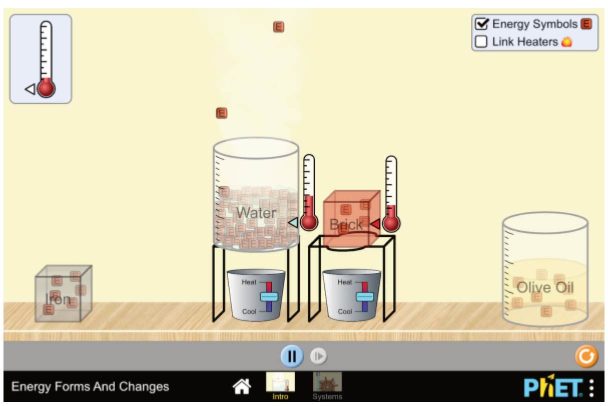
According to data on energy densities in fuel, typical liquid fuels (white gas, gasoline, etc.) will provide roughly 40 **MJ** (40,000,000 **J**) of net heating energy per **kg** of fuel burned. To make our rough estimate the *minimum* fuel requirement we will assume all of the thermal energy released by burning the fuel is transferred to the water:

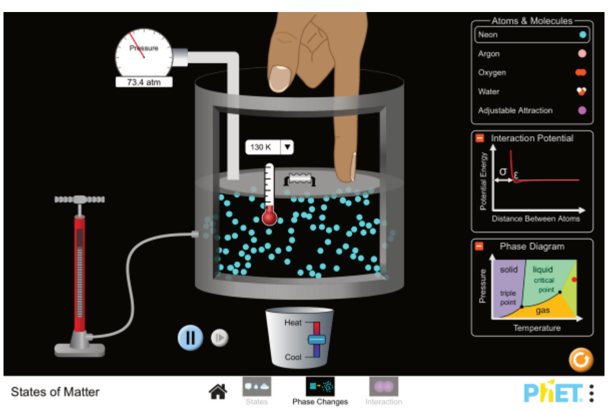
$$Fuel\ Mass = \frac{187,076,736\,\mathbf{J}}{40,000,000\,\mathbf{J}/\mathbf{kg}} = 4.7\,\mathbf{kg}$$

The density of liquid fuels is less than water at roughly 0.75 **kg/L**, so this minimum 4.7 **kg** of fuel comes out to about 6 liters, or 1.5 gallons. Accounting for heat loss from stove and pot to the environment (especially in windy conditions) the actual requirement could end up substantially greater, depending on conditions. On an actual 3-person, 21-day expedition to the summit of Denali in May of 2012 we used just under 2 gallons of fuel, so our estimate was pretty reasonable.

Reinforcement Exercises

Check out the following simulations allows you to play with phase changes.





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CHAPTER 97.

HEAT DEATH

THE SECOND LAW OF THERMODYNAMICS REVISITED

The Second Law of Thermodynamics introduced in the previous chapters states that *thermal energy will always spontaneously transfer from higher temperature to lower temperature*. In order to aid in our study of other thermodynamic processes, such as phase changes, a more general version of the Second Law can be stated in terms of energy concentration and dispersion: a*ny spontaneous process must move an isolated system toward a state of more uniform dispersion of energy throughout the system*. By isolated system we mean one for which energy does not leave or enter. For example, we know that higher temperature means a greater average thermal energy per molecule, so we can think of temperature as a measure of the concentration of thermal energy in an object. If we consider a hot object in a cold room as our complete system, then the thermal energy in our system is not very well dispersed because it's more concentrated in the hot object. The Second Law of thermodynamics predicts that energy should move from the hot object to the cold environment to better disperse the energy, and that is what we observe. However, the heat transfer will only occur until the thermal energy is maximally dispersed, which corresponds to thermal equilibrium, and is indicated by the object and environment having the same temperature.

Everyday Examples: Sweating, Dew, and Rain

When we sweat to exhaust thermal energy by evaporation we aren't actively grabbing the hottest water molecules, pulling then away from their neighbors, and throwing them into the gas phase. The evaporation happens s*pontaneously* because thermal energy stored in water molecules that are stuck together is relatively concentrated compared to thermal energy stored in water molecules zipping around in the air and free to disperse. The transfer of thermal energy to sweat (by conduction), followed by evaporation is a spontaneous process because it increases the dispersion of energy throughout the system made up of you, the sweat, and the surrounding air. Therefore, evaporation of sweat is a spontaneous process.

When the relative humidity reaches 100% then evaporation has maximally dispersed the available thermal energy. Any additional evaporation would begin to over-concentrate energy in the air and decrease the overall level of energy dispersion. Therefore, we don't see evaporation occurring once 100% humidity is reached. In fact if the humidity gets pushed above 100% (by a drop in air temperature without a loss of water vapor) then energy is over-concentrated in the air and thus increasing dispersion of energy requires that water molecules come out of the vapor phase and condensation occurs spontaneously. When the liquid condenses on surfaces we call it dew, when the liquid condenses on particles in the air and falls to the ground we call it rain.

Reinforcement Exercise

ENTROPY

Entropy (*S*) is a measure of energy dispersion within a system. An increase in the entropy corresponds to an increase in dispersion of energy. A decrease in entropy would correspond to energy being less dispersed, or increasing energy concentration. Therefore the Second Law of Thermodynamics can also be stated as: *a process will happen spontaneously if it increases the total entropy of an isolated system*. The change in entropy for a constant-temperature process can be calculated from the heat transferred (*Q*) and the temperature at which the transfer occurs (*T*) as:

(1) $\Delta S = Q/T$

Notice that we definitely need to use the Kelvin absolute temperature scale when working with the change in entropy equation, or else we might find ourselves attempting to divide by zero. Let's apply this equation and the entropy version of the Second Law of Thermodynamics to the second part of the previous Reinforcement Exercise.

Everyday Example: Entropy Change of Melting

If you place ice in a warm room and leave it alone, it will melt. The ice melting would be a spontaneous process because it will happen all on it's own, so we should find that melting increases the total entropy ($\Delta S > 0$). Let's check that out. We'll keep it simple and calculate change in entropy of one kilogram of ice, which melts at 0 **°C**, or 273 **K**.

$$\Delta S_{ice} = Q/T = \frac{mL_f}{T} = \frac{(1\,\mathbf{kg})(334,000\,\mathbf{J}/\mathbf{kg})}{273\,\mathbf{K}} = 1223\,\mathbf{J}/\mathbf{K}$$

Next we calculate the change in entropy for the room. The same heat that went *into* melting the ice came *out* of the room, so the *Q* for the room is the same as for the ice, only negative. Let's pick a typical room temperature of 20 **°C** for our example, which is 293 **K**:

$$\Delta S_{room} = Q/T = \frac{-mL_f}{T} = \frac{-(1\,\mathbf{kg})(334,000\,\mathbf{J}/\mathbf{kg})}{293\,\mathbf{K}} = -1140\,\mathbf{J}/\mathbf{K}$$

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Now we just add up the two entropy changes to get the total:

$$\Delta S_T = \Delta S_{ice} + \Delta S_{room} = 1223\,\mathbf{J/K} + (-1140)\,\mathbf{J/K} = 17\,\mathbf{J/K}$$

Our entropy change is greater than zero, so the Second Law states that ice melting in warm room is a spontaneous process, which we observe it to be.

MAXIMUM EFFICIENCY

Spontaneous processes are inherently irreversible. For example, we could not reverse the spontaneous process of thermal energy transfer from your body to sweat and then to the environment by evaporation. Imagine trying to run around and grab all the water vapor molecules and shove them back into the liquid on our skin and then make those water molecules collide with skin molecules in just the right way to conduct thermal energy back into your body! Good luck. If the process could be reversed, the net entropy change would be zero, but that is not a real possibility. Any *real process* increases the entropy because irreversible at some level, meaning energy is further dispersed throughout the system without a realistic opportunity to put it back where it was. We have arrived at yet another version of the Second Law of Thermodynamics: a*ny real process increases the total entropy of the universe.* For example, even if you could reverse the evaporation process we described above, the exhaust heat you released during that running around would decrease the concentration of energy in your body and disperse it throughout the room.The system, which includes you, would not cause have returned to the original conditions at all. In fact, the total entropy would have increased by even more than before you tried to reverse the process. For example, as you ran around, more sweat would have evaporated and you would have to chase those molecules down as well, and so on–you could never win! We can't keep the entropy of the universe from increasing.

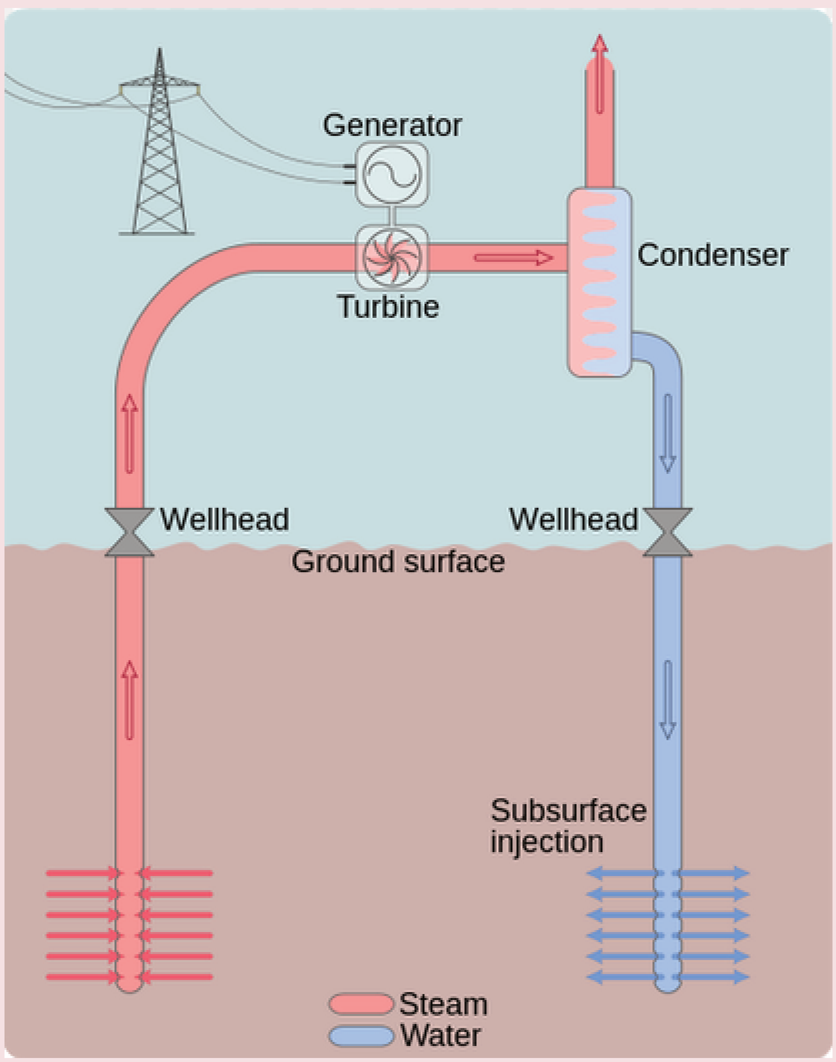
Everyday Examples: Human Mechanical Efficiency

Muscle contraction relies on the release of chemical potential energy stored in ATP molecules. Before contraction, that energy is concentrated into certain molecules in certain areas of a muscle cell. When that energy is released, the entropy of the molecules decreases, so the entropy of their environment must increase by more, and this is achieved because most of the energy released from the ATP molecules is degraded to heat and distributed to the environment. After contraction, a muscle cell must be reorganized, which decreases entropy, but we know overall entropy must increase for any real process, so some additional thermal energy must be dispersed to the environment during reorganization in order to provide the necessary entropy increase. All of this thermal energy is "wasted" because it is came from stored chemical potential energy, but is not available for use by the body to do work. Therefore, entropy and the Second Law of Thermodynamics limit the efficiency of the human body.[1]

1. "Thermodynamics of Skeletal Muscle Fiber: Do We Need to Redefine "Active" and "Resting" States?" by I. Y. Cristlieb and E. Cesarman, Cadiovascular and Pulmonary Research Center, The Medical College of Pennsylvania/Hahnemann University

Everyday Example: Geothermal Heat Engine

Let's imagine molten rock from the Earth's mantle pushes partway through the Earth's crust, and keeps a region of bedrock at a constant temperature of 300 **°C** . If the rock was not too deep, we could install pipes in the rock, and then boil water by running it through the pipes. We would basically have a giant pressure cooker! Rather than cook food, we could release the pressurized steam to push on a piston or spin a turbine. After releasing the pressure and getting some work out, we would be left with lower pressure steam. We could condense the steam back to water by running it through pipes exposed to the 20 **°C** air above ground. Thermal energy would transfer from the steam to the air as exhaust heat, the steam would condense into liquid water, and we could start again.



The dry steam cycle from "Geothermal power plants" by Energy Education, University of Calgary

Machines like the one described that convert thermal energy into mechanical energy are called a heat engines. Your car is powered by an internal combustion heat engine. Let's see how entropy and the Second Law of Thermodynamics determine the efficiency of our geothermal heat engine.

First we calculate the entropy change when 1000 **J** of thermal energy transfers out of the rock to the water to run the engine, remembering to convert the 300 **°C** rock temperature to Kelvin by adding 273 **K**:

$$\Delta S_{rock} = \frac{Q_{rock}}{T_{rock}} = \frac{-1000\,\mathbf{J}}{573\,\mathbf{K}} = -1.75\,\mathbf{J/K}$$

If our engine is real, then so are its processes, which means that running the engine must increase the total entropy of the universe, according to the Second Law of Thermodynamics. We need to find out how much thermal energy must be transferred from the low pressure steam into the air at 30 **°C** (293 **K**) in order for the entropy of the air to increase by at least as much as the rock entropy decreased (1.75 **J/K**). We can find this by rearranging the change in entropy equation and inserting a positive entropy change that is equal in size to the the negative change experienced by the hot rock:

$$Q_{air} = \frac{T_{air}}{\Delta S_{air}} = \frac{293\,\mathbf{K}}{1.75\,\mathbf{J/K}} = 511\,\mathbf{J}$$

Transferring the 511 **J** of thermal energy into the air leaves only 489 **J** of the original 1000 **J** input energy available for doing work. Therefore the maximum possible efficiency of our engine is limited, no matter how well designed, even if all mechanical inefficiencies like friction could some how be eliminated. The maximum theoretical efficiency is:

$$e = \frac{Work}{Input\ Energy} = \frac{489\,\mathbf{J}}{1000\,\mathbf{J}} = 0.49$$

Multiplying by 100 **%** would give us the efficiency as a percentage: 49 **%**. This is a maximum possible efficiency. Any engine we actually built would be less efficient.

The First Law of Thermodynamics told us that you cannot build an engine that is more than 100 % efficient because energy cannot be created. Even worse, the Second Law tells us that even if we managed to eliminate all mechanical inefficiencies, such as friction, we still can't get up to 100 % because all engines must exhaust some energy in order to increase entropy overall. The theoretical maximum efficiency, which is always less than 100 %, is known as the Carnot efficiency (e_c) and depends only on the high and low operating temperatures (T_H and T_L), as we saw in the previous example. Most of the work we did in the previous example can be short-cut by the equation for Carnot Efficiency (e_c):

$$e_c = 1 - \frac{T_L}{T_H} \quad (2)$$

The theoretical engine which could actually produce that theoretically maximum efficiency is known as the Carnot Engine. The operating principles of the Carnot Engine are well known, having been developed by Nicolas Léonard Sadi Carnot in 1824, but the engine cannot be realistically designed or built.[2]

2. "Carnot heat engine" by Wikipedia

Reinforcement Exercise: Carnot Efficiency

Check that the previous short-cut equation gives the correct maximum efficiency for our geothermal heat engine.

What is the Carnot efficiency of our geothermal heat engine if the hot rock was actually at 550 **C°** instead of 300 **C°** ?

You will find that this engine is more efficient just because the hot operating temperature higher, even though it still works in the same way and nothing else has changed. The efficiency increased because the input energy started out more concentrated and less dispersed (indicated by higher temperature), so less of that energy had to become dispersed in the environment, or wasted, in order to ensure that entropy increased by a sufficient amount to satisfy the Second Law of Thermodynamics. Thermal energy that starts out concentrated (at high temperature) is known as *high quality* energy.

Reinforcement Exercise:

HEAT DEATH

In addition to limiting our efficiency in doing mechanical work, the Second Law drives our bodies toward higher entropy, which means thermal equilibrium with the environment. Unless the environmental temperature happens to be near body temperature, reaching thermal equilibrium means death. Life also requires concentration of chemical potential energy, but due to the the Second Law we tend toward chemical equilibrium, which is not survivable. Concentrations of electrical energy drive your nervous system, but due to the Second Law we are constantly at risk of reaching an internal electrical equilibrium with no electrical activity. Life is a constant battle against various types of equilibrium that would correspond to maximum entropy, but also to death. The work necessary to fight off our own entropy increase is what we consider basic metabolism. Doing that work, and even taking in the energy required to do that work, involves real processes that provide even more opportunity for entropy increases in a seemingly viscous cycle. You can't beat the Second Law of Thermodynamics! Even as we manage to prevent our own entropy increase we cause the entropy of the environment to increase by a greater amount than what we prevented in ourselves. In fact, a complete dispersion of energy, so that all matter is at equilibrium, and no processes remain which would increase the entropy, and nothing really happens all, is one possible fate of the universe which has been dubbed *heat death*. At least we don't expect heat death of the universe to occur for at least 10^{100} years. [3]

An interactive or media element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=2730

3. OpenStax, College Physics. OpenStax CNX. Mar 6, 2019 http://cnx.org/contents/031da8d3-b525-429c-80cf-6c8ed997733a@14.78

CHAPTER 98.

UNIT 10 REVIEW

Key Terms and Concepts

Temperature

Thermal expansion

Thermal energy

Heat

Conduction

Forced Convection

Natural Convection

Thermal Radiation

Heat capacity

Phase change

Latent heat

Entropy

Second Law of Thermodynamics

Heat Engines

Efficiency

Learner Objectives

1. Compare, contrast, and convert between absolute and relative temperature scales.[1]
2. Evaluate the effectiveness of various types of insulation against different mechanisms of heat transfer.[3]
3. Apply the concepts of temperature, thermal expansion, specific heat, heat capacity, and latent heat, to analyze how physical objects respond to heat transfer.[3]

4. Apply the Second Law of Thermodynamics to predict the outcome of physical scenarios.[2]

CHAPTER 99.

UNIT 10 PRACTICE AND ASSESSMENT EXERCISES

Outcome 2

Babies, and especially premature babies, have particularly large surface area relative to their body mass as compared with adults. That makes them especially susceptible to hypothermia. Incubators are used to help reduce the heat loss rate in such cases. What are the basic features of an incubator and how do they reduce heat loss by each of the following:

Thermal Radiation

Conduction

Forced Convection

Evaporation

Outcome 1

Human body temperature is 98.6 °**F**. Convert this to Celsius.

Convert body temperature to Kelvin.

Outcome 3

The surface area of a premature baby can be calculated according to the formula of Haycock *et. al.*[1]

Surface Area = M 0.5378 x L 0.3964 x 0.024265

The result give are in $\mathbf{m^2}$**,** but length (L) is input in **cm** and mass (M) is input in **kg**

Calculate the surface area for a premature baby with weight of 3.5 **lbs** (a mass of 1.8 **kg**) and length 42 **cm**.

Use the surface area and body temperature you found above to calculate the rate at which the baby loses thermal energy to the environment by thermal radiation if the room is at a temperature of 75 °**F**

1. "Body Surface Area Calculator" by , NICU Tools

(23.9 **°C**). The emissivity of human skin is typically 0.98. Don't forget convert the room temperature to Kelvin.

Calculate the heat loss rate by conduction to the table if the baby is laying on a mattress 5 **cm** thick with thermal conductivity of .04 **W**/ (**m °C**). Use the same body temperature and room temperature as in the previous calculations. Assume only the back half of the body is experiencing conduction (use half the surface area).

Calculate the heat loss rate by forced convection for an air speed of 0.5 **m/s** is caused by the ventilation system and movement of people in the room etc. Use the same body temperature and room temperature as in the previous calculations. Assume only the front half of the body is experiencing forced convection (use half the surface area).

If the room is at 50 **%** relative humidity the air speed of of 0.5 **m/s** will result in an evaporation from the baby's moist skin at a rate described by the equation below (we didn't talk about determining evaporation rate so if you want to understand this equation talk with you instructor, but for now just use it).

Rate of evaporation in **kg/s** = 0.000097 x surface area.

Calculate the rate of evaporation of water from the baby's skin.

What is the rate at which this evaporation removes thermal energy from the baby? (Hint: How much energy is lost for each **kg** of water that evaporates?)

Add up all of these heat loss rates to get the total rate of heat loss.

Assuming the baby is mostly water, (use the specific heat of water) calculate the rate at which the temperature of the baby will change in **C°** per second. Use the baby mass from above.

How many degrees would the baby's body temperature lower in 10 minutes at this rate?

Connecting Concepts: Metabolism, Thermal Power, Heat

Let's imagine that we thought the baby could handle generating the thermal energy needed to replace the heat loss you calculate above by simply converting food Calories into thermal energy. In that case we wouldn't need an incubator, we would just need to keep the baby well fed. How much breast milk would the baby need to drink each day? Let's find out.

Breast milk has 700 Calories (**kcal**) per **kg**. [2] How many **kg/s** of milk would the baby need to drink to intake the same energy as what is lost?

How many **kg**/hour is this?

How many **kg**/day is that?

How does that compare to the baby's mass?

Does this seem reasonable? Explain.

2. "Basic Report: 01107, Milk, human, mature, fluid" by Food Composition Database, US Department of Agriculture

PART XI.

LABORATORY ACTIVITIES

General Design

The labs provided here are designed to create a lab-based or "work-shop" type of experience even when scheduling limitations force a standard lecture + lab course format, as is the case for many community colleges. As such, the labs follow a heavily guided inquiry format, which allows for inquiry based learning by inexperienced students while ensuring leaner outcomes are practiced and assessed. Students will make predictions, work hands on with equipment to acquire and analyze data, and compare predictions to results. Students are not asked to design large portions of experiments themselves, though they may be asked to suggest possible ways to test predictions or explain how they would make improvements to methods. Most students will require significant assistance in completing the labs, especially the analysis portions. As such, these labs may be best suited for courses in which the primary instructor is also the lab instructor.

Timing

The labs are designed to be completed in a 2 **hr** and 50 **min** lab session, but in some cases additional analysis work might carry over into classroom sessions. This helps to connect the lecture and lab components of the course and brings hands-on activities into the lecture environment.

Mix and Match

Of course instructors edit the labs to match content and cognitive level with their own course outcomes and/or should mix their favorite parts of the labs with other activities they find useful.

CHAPTER 100.

UNIT 2/3 LAB: TESTING A TERMINAL SPEED HYPOTHESIS

TERMINAL SPEED

Materials:

- lab sheet and writing utensil
- calculator
- 10 Coffee filters
- step ladder allowing you (or a partner) to reach 2 **m**
- ruler with **cm** units
- scale with at least 0.1 gram precision
- spreadsheet and graphing software
- for distance learners, access to online forums, videos, and help features for the spreadsheet software will likely be necessary
- one of the following equipment sets:
    - motion sensor + computer with control and analysis software
    - video motion analysis app (example)
    - camera (slow motion mode preferred) + stopwatch with 0.01

Course Outcome 5, Unit Outcome 2-1

Observation

We observe that when a body falls through the air it eventually reaches a maximum speed, known as terminal speed, which is roughly 200 **mph**.

Question

This phenomenon raises the question: What determines the value of the terminal speed?

Search Existing Knowledge

Find an answer for what determines the value of the terminal speed. Write the answer below and also list your source.

Hypothesis

Our search of existing knowledge told us that one factor affecting terminal speed was the mass of the object.

Provide a qualitative hypothesis on how the terminal speed depends on the mass of an object. That means to state if you think the terminal speed will increase or decrease when mass increases. Explain your reasoning.

Test

To test your hypotheses, without jumping out of airplanes, we will measure the terminal speed of coffee filters with varying mass. The terminal speed for coffee filters is much slower than for bodies and they will typically reach terminal speed in less than 2 meters of drop distance. These properties will make our experiment reasonable to perform in the lab. Your hypothesis was about an object's terminal speed and mass in general, not about bodies specifically, so a coffee filter experiment will still test your hypothesis.

Measure the mass of the coffee filter and record here:___________

Our method will be to drop coffee filters from a height of at least 2 **m** and measure the terminal speed. You will need a step ladder and a partner to make the measurements. You can measure the terminal speed using photogates or acoustic or laser based motion sensor if you have access to those in your lab. If not, you can measure the terminal speed by using a video motion analysis app, or by simply filming the last 0.1 **m** (10 **cm)** of the fall while holding a ruler and a running stopwatch to be visible in the video frame.

If using the motion sensor, be sure to only use the section of the speed data after the speed has become constant and before impact. Your instructor will help you find this section of data. Record your terminal speed here:______________

If using the filming method, be sure to film straight on to the ruler, which should be standing up straight on the floor. Read off the time off the stopwatch in the video when the filter passes the 10 **cm** mark and again when it hits the floor. Subtract the first time from the second to find the difference between these times. Divide 0.10 **m** by the time difference to get the terminal speed. Record your terminal speed here:______________

Repeat this experiment for two nested (one inside another) coffee filters. Nesting the coffee filters increases the mass, but doesn't change the shape of the filters, allowing us to change only one variable at at time. Record your terminal speed for two filters in the chart. Also measure the mass of the two filters and record in the chart as well.

Repeat the experiment until you have measured terminal speed and mass for at least 5 nested coffee filters. Record the number of filters and terminal speed for each in the table below:

Number of Filters	Terminal speed (m/s)	Mass (g)
1		
2		
3		
4		
5		
6		
7		
8		
9		

Analyze

Enter your data into a spreadsheet and create an x-y graph of terminal speed vs. mass. Mass should be on the horizontal (x-axis) because mass is the independent variable (what you are purposefully changing). Speed should be on the vertical axis (y-axis), because speed is the dependent variable (what is changing in response to the independent variable).

Be sure to give your graph a title and label the axes with the variable names and the units of measure.

Check with your instructor to find out if they want you to enter your group's data into the class-data spreadsheet.

Conclusion

Was your qualitative hypothesis supported by the data? Explain.

Be sure to save your spreadsheet and graph. We may use them again during this course.

Hypothesis Testing Including Uncertainty*

In order to really answer the question about whether or not the experimental results support the hypothesis we need to think about uncertainty. (Unit outcome 3-4)

Let's do a little experiment to determine how random error affects the precision of your results. Repeat the final filter set measurement 6 more times and record the results, including the first value you found above, in a chart:

Use your spreadsheet software (or some other method) to take the average and the standard deviation of the seven values. Record both below:

The standard deviation value will serve as an estimate of the precision in our experiment. A new measurement should be within the standard deviation of the average value 68 % of the time. We will use the precision provided by the standard deviation as our estimate of the uncertainty in our final measurement. Ideally we would base our average and standard deviation on more than seven values, but we will use only seven in this learning situation for the sake of time.

Add error bars to the terminal speed data in your graph, setting the size equal to the standard deviation you calculated.

Considering the error bars, does the data support your qualitative hypothesis? Explain your reasoning.

So far we have ignored systematic error. Systematic errors can be difficult to recognize and even more difficult to quantify. We must always be on the look-out for sources of systematic error.

Can you provide a possible source of systematic error in your experiment? Explain. (Unit outcome 3-2)

Can you estimate how large the error might be (provide an upper bound) Explain. (Unit outcome 3-3)

Modeling

As a class we will fit a curve to our data of terminal speed vs. mass of filters and use the equation of that curve to predict the terminal speed for a higher number of filters. (Outcome 2-2)

What type of model is this? Explain.

Write the fit equation we found here:

Record the number of filters and mass of the filter set you will predict/test:

Show your work in calculating the predicted terminal speed for additional filters.

Drop your new filter set and record the terminal velocity you measure:

Did the prediction agree with the experimental test within your uncertainty? Does your result add validity to your model? Explain.

CHAPTER 101.

UNIT 4 LAB: HYDROSTATIC WEIGHING

HYDROSTATIC WEIGHING

Materials:

- graduated cylinder (required for displacement method, but not required for hydrostatic weighing method)
- plastic bin to contain spills
- object to submerge
- calculator
- scale with at least 0.1 gram precision
- spreadsheet and graphing software
- for distance learners, access to online forums, videos, and help features for the spreadsheet software will likely be necessary
- force sensor + computer with control and analysis software OR spring scale with 0.1 gram precision (required for hydrostsatic weighing method, but not for required for displacement method)

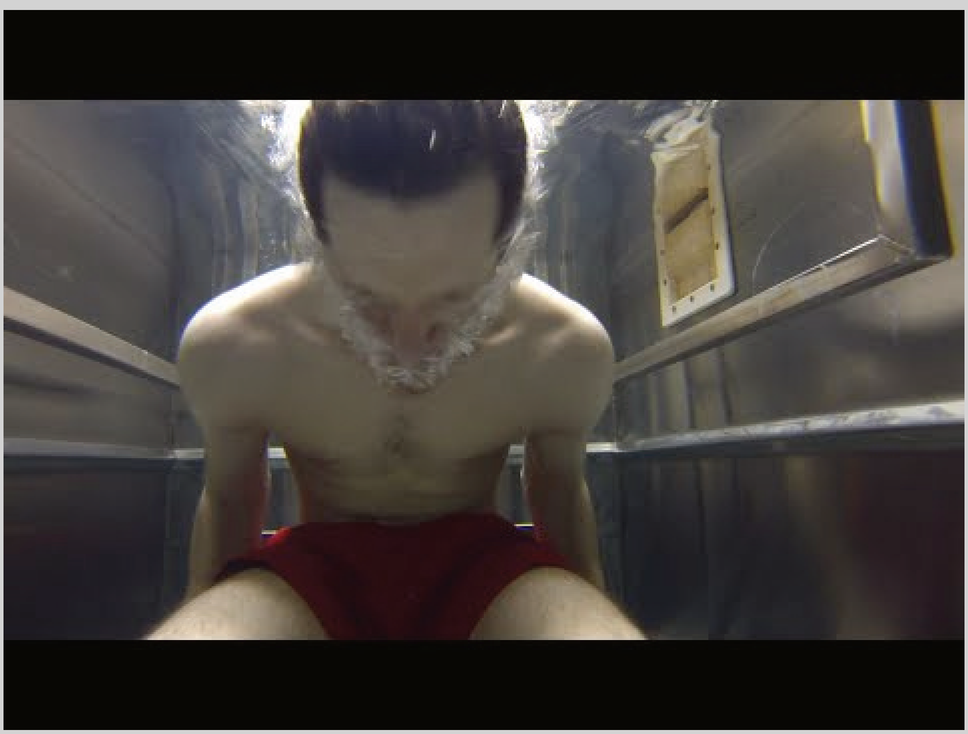
Objective

The objective of our lab is to determine the density of an object in the same way we would for a person. We will determine body density in two ways, one being the displacement method and the other being hydrostatic weighing.

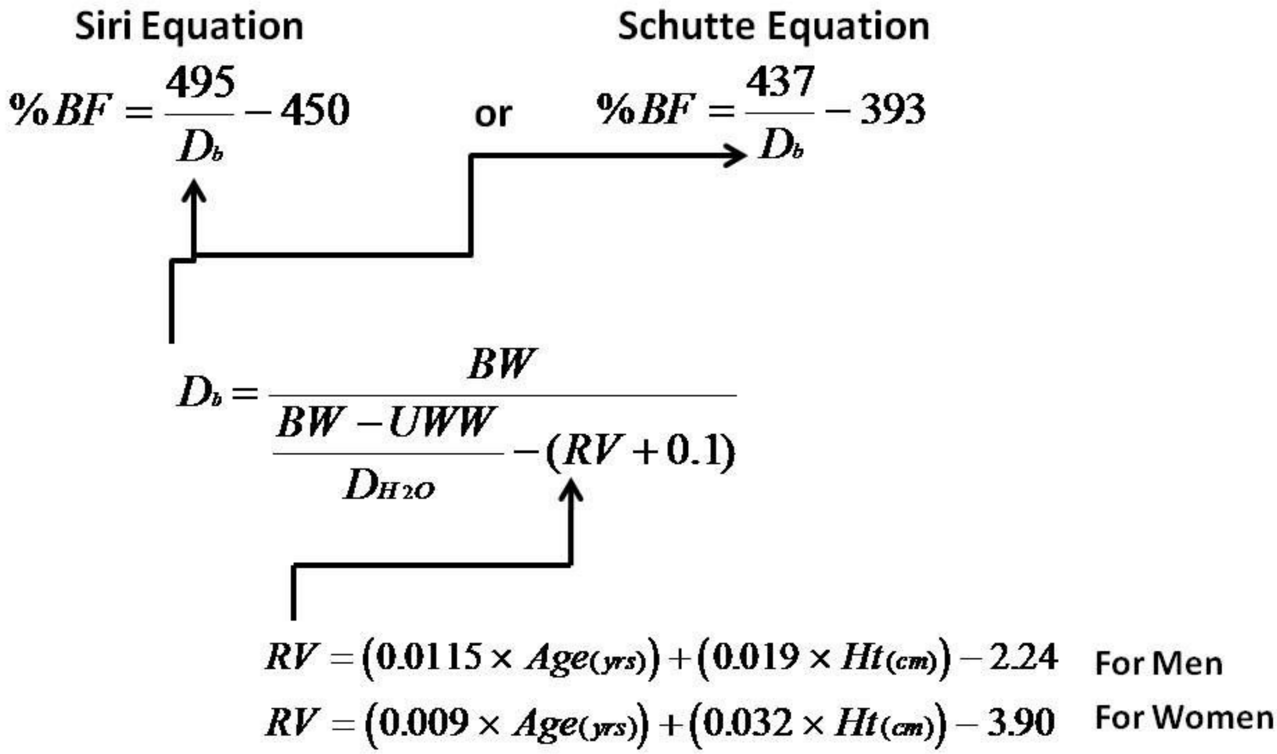
You might want to watch this video to refresh your memory regarding the general process for hydrostatic weighing:

General Methods

The video above does not explain how to actually calculate the body fat percentage (*BF%*) from the hydrostatic weighing data. The BF% calculation is done using rather a complex empirical model that requires body density, D_b, as an input. Hydrostatic weighing allows us to determine density to use in the model. The model looks like this.



A YouTube element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=1370



Formulas for calculating body fat percentage from body density and other body measurements. Image Credit: MattVerlinich via Instructables

[1]

Body density is calculated from body weight (BW), under water weight (UWW), water density (D_{H2O}) and residual lung volume (RV). The hydrostatic weighing process provides BW, UWW, and D_{H2O}. Residual lung volume can be calculated from empirical equations that depend on age, height, and gender. We will not need to account for RV or residual intestinal gasses (the 0.1 value in the D_b equation) today because our object is solid.

For fun we will use the body density value we find as an input to calculate the “body fat percentage” of our object, but of course this number will not be meaningful because the final BF % formula we are using is an empirical model based only on data from people.

Displacement Method (requires graduated cylinder)

Outcome 4-1

Measure the body mass of your object and record here:__________

If your measurement device only provided you with body weight, then calculate the body mass. You

1. "MEASURE BODY FAT % VIA UNDERWATER WEIGHING" by MattVerlinich, Instructables, Autodesk

may need to look up the equation relating mass and weight of an object near the surface of the Earth. Show your work.

Submerge your object in the graduated cylinder and measure the change in volume. This is the volume of water displaced by the object.

Record displaced volume here:__________

How does the volume of displaced water compare to the volume of the object? Explain your reasoning (remember, the object was completely submerged).

Outcome 4-4

Use your recorded mass and volume to calculate the density of your object. Show your work.

Hydrostatic Weighing Method (requires force sensor or spring scale)

Measure the body weight of your object in air and record here:___________

If your measurement device provided you with mass instead of weight, then calculate the object weight. You may need to look up the equation relating mass and weight of an object near the surface of the Earth. Show your work.

Submerge the object and measure the under water weight, also known as the apparent weight. Record here:___________

Again, if your measurement device provided you with mass instead of weight, then calculate the object weight. Show your work.

Based on your measured weight and apparent weight, what must be the size of the buoyant force?

Use Archimedes' Principle to determine the weight of the water displaced by the object. Explain your reasoning.

Calculate the mass of the water displaced. You may need to look up the equation relating mass and weight of an object near the surface of the Earth. Show your work.

Look up the density of water and record here:________
Now use the definition of density to find the volume of the displaced water. Show your work.

How does the volume of displaced water compare to the volume of the object? Explain your reasoning (remember, the object was completely submerged).

Now you know the body volume of the object, so if you know its body mass then you can calculate its body density. Calculate the body mass from body weight you found earlier, and then calculate body density. Show all work.

Does the formula result agree with your result from the mass/(displaced volume) method?

The work you just did recreated the complicated formula for D_b shown at the front of the lab (except for the residual body gasses part)! Now that we know how it works, from now on we can just use the formula instead of going through the extra steps. Just to make sure, use the D_b formula to calculate density of your object, (only leaving out the part accounting for residual body gasses). Show your work.

Does the formula result agree with your result from hydrostatic weighing and mass/ (displaced volume)?

Body Fat Percentage

Use the body fat percentage formula at the start of the lab to calculate the body fat percentage of your object. Show your work. Does the result seem reasonable? Explain. If not, any thoughts on why?

CHAPTER 102.

UNIT 5 LAB: FRICTION FORCES AND EQUILIBRIUM

FRICTION FORCES AND EQUILIBRIUM

Materials:

- lab sheet and writing utensil
- calculator
- small board, box, book, or other object to slide across the table
- string
- pulley with clamp
- set of known masses
- spreadsheet and graphing software
- force sensor + computer with control and analysis software

Course Outcomes 4, 5
Unit Outcome 2-1

Observation

Is it more difficult to start an object sliding than it is to keep it sliding? Give it a try and state your observation.

Question

Finish generating a question about your observation: Why is it that____

Search Existing Knowledge

Find an equation that shows what factors the frictional force depends on. Write it down below and list your source. The equation you found represents what type of model? (Quantitative or Qualitative and Empirical or Physical)

Hypothesis

Based on what you found above and your observation/question, provide a hypothesis about which is larger between the static friction coefficient and the kinetic friction coefficient. Explain how your observation and the information you found above were used to create the hypothesis.

Test

To test your hypotheses we determine the static and kinetic friction coefficients between an object and the table.

Our method will be to use the force sensor to measure the weight of the object. Then use the force sensor to measure the force needed to slide the object, and keep it sliding at the same speed. Be sure to **zero the force probe** in the orientation you will use it before making each one of your measurements.

Use the string to hang your object from the force probe and record the weight of your object here:________________.

Unit Outcomes 5-1, 5-4

Use the concepts of tension force and static equilibrium to explain how you know that the reading on the force probe was equal to the weight of the object.

What is the normal force on the object from the table when it is sitting on the table? Explain how you know using the concept of static equilibrium.

Does the normal force change if the book is sliding across the table? [Hint: Does the book ever start moving vertically?]

Now you will use the string to connect the object to the force probe and then gradually increase how hard you pull horizontally on the object until it finally begins to slide. After it begins to slide, keep pulling the object at a constant speed for at least five seconds. Practice this a few times before you begin taking data.

Now that you have practiced, zero the force probe in the horizontal orientation that you will pull, and record the force measured by the probe while you pull horizontally on the object until it finally begins to slide and continues at a constant speed for at least five seconds.

Record the maximum force registered by the force probe:_______________

This is the size of the maximum frictional force applied before the object started to move, or the static frictional force. Explain how the concept of static equilibrium tells us that the maximum reading on the probe is the static frictional force.

Use the static friction force and your known normal force from above to calculate a static friction coefficient. Show your work.

Record the average force registered by the force probe after the object started to slide:_______________

You pulled the book with a constant speed and direction so it was in dynamic equilibrium and the forces must be balanced. Therefore the pull force you measured with the force probe must have been equal to the kinetic frictional force.

Use the kinetic friction force and your known normal force from above to calculate a kinetic friction coefficient. Show your work.

Repeat the experiment 6 more times, calculating a static and kinetic friction coefficient each time. Create a chart to keep track of your data. You may want to create a spreadsheet to calculate the coefficients from the force measurements so that you don't need to do it by hand each time and because you will be calculating average and standard deviations of your measurements.

Calculate the average static friction coefficient and average kinetic friction coefficient and record these below:

Unit Outcomes 3-4

Also calculate a standard deviation for each set of coefficient measurements. Record this below:

Using the standard deviation as the uncertainty in your measurements, do the average static and kinetic coefficients differ by more than the uncertainty? Explain.

Unit Outcome 2-1

Conclusion

Do you conclude that the static coefficient is larger, the kinetic coefficient is larger, or they are the same? Explain.

Was your qualitative hypothesis correct? Explain.

CHAPTER 103.

UNIT 6 LAB: ELASTIC MODULUS AND ULTIMATE STRENGTH

STRENGTH AND ELASTICITY

Materials:

- lab sheet and writing utensil
- calculator
- thin (roughly 1 **mm** x 1 **mm**) rubber band and place to hang it (e.g. cabinet handle)
- Ruler with **mm** precision
- spreadsheet and graphing software
- for distance learners, access to online forums, videos, and help features for the spreadsheet software will likely be necessary
- one of the following equipment sets:
  - force sensor + computer with sensor control and analysis software
  - collection of weights with hooks, from 0.01 **kg** to 1 **kg**

(Course outcomes 4, 5; Unit outcome 6-3)

Observation

Rubber bands behave elastically and they also appear to have a "crimping" behavior similar to tendons. When relaxed the bands tend to curl up and it takes a small force to straighten them out, then once straight, they provide more resistance to being stretched.

Question

Are rubber bands a good model for tendons?

Search Existing Knowledge

Find an example stress-strain curve for a tendon. What is the name of the region caused by "crimping" behavior? What is the elastic modulus of human tendon? What is the ultimate strength of human tendon? List your sources for this information.

Hypothesis I

Provide a qualitative hypothesis that compares the stress-strain behavior of rubber bands and tendons. That means to state which regions of the stress-strain curve for a tendon you expect will also appear in the rubber band curve. Explain your reasoning.

Hypothesis II

Also generate a hypothesis about whether rubber bands or tendons have will have a larger ultimate strength. Explain your reasoning.

Hypothesis III

Also generate a hypothesis about whether rubber bands or tendons have will have a larger elastic modulus. Explain your reasoning.

Test

To test your hypotheses you will create a stress-strain curve for the rubber band.

Our method will be measure the stretch distance as additional force is added to the band. In order to determine stress and strain we will need to know the original length and cross-sectional area of the rubber band.

Hang the rubber band from a cabinet handle, ring stand, or other feature capable of supporting about 20 **lbs** (or enough force to rupture your rubber band). If you are using a rubber band larger than 1 **mm** x 1 **mm**, then you may have a difficult reaching the ultimate strength of the rubber band:

*Photograph of a 1 mm x 3 mm rubber band during stress testing. The band runs through the slots in the gray weights and the hook attached to the bottom of the band is just visible through the slot in the lowest group of smaller (0.98 **N**) weights. The 119 **N** of force is applying 1.3 x 10^{13} **Pa** of stress, causing a strain of 660 %. Photo credit: Umpqua Community College student Samual Marsters.*

Use your ruler to measure the relaxed length of the hanging rubber band and record here:_________

Measure the width and thickness of the rubber band and multiply to get the cross-sectional area. Record the measurements here: Width_________ Thickness___________ Show your work in calculating the cross-sectional area below:

Convert your area to square meters (**m^2**), show your work below:

If you are using a force sensor, be sure to zero the sensor in the vertical orientation. If you are using pennies, determine the weight of a single penny in units of Newtons, if you are using known masses then remember to calculate their weights as you go.

Now we will pull on the band with the force sensor (or pennies or weights) and measure the force and length, then use the initial length and area to calculate stress and strain. Start with your smallest weight and work up so that you can determine if there is crimping behavior. Be sure to pull hard enough or add enough weight so that the length changes by at least 2 **mm**, (so the change is not obscured by the uncertainty in your length measurement). Continue until the rubber band begins to rupture. Record the results in the chart below.

Hanging Mass (**Kg**)	Force (**N**) (from force sensor, or weight of pennies)	Length (**mm**)	Stress (**N/m^2**)

Analyze I

Enter your data into a spreadsheet and create an x-y graph of stress vs. strain.

Be sure to give your graph a title and label the axes with the variable names and the units of measure.

Conclusion I

Was your qualitative hypothesis comparing the shapes of stress-strain curves for tendons and rubber bands correct? Explain, referencing your graph and the various regions.

Analyze II

What was the ultimate strength of the rubber band? Record here:__________

Conclusion II

Was your hypothesis comparing the ultimate strength of rubber bands and tendons supported by your data? Explain.

Analyze III

We need to find the elastic modulus, which tells us how the material resists strain. The elastic modulus is defined as the slope of the elastic region of the stress-strain curve. You can find the slope two ways:

1) slope is defined as rise over run. Find the how much the stress changes across the elastic region, then divide this by how much the strain changes across the elastic region. 2) graph only the data from the elastic region and use the spreadsheet to fit a line to the data. Don't forget to ask your instructor or TA for help if you need it.

Write the change in stress across the elastic region here:__________

Write the change in strain across the elastic region here:__________

Show your work in calculating the slope below:

Write your slope here:_______________. The slope of the elastic region is the elastic modulus.

Conclusion III

Was your hypothesis comparing the elastic modulus of rubber bands and tendons supported by your data? Explain.

CHAPTER 104.

UNIT 7 LAB: ACCELERATED MOTION

ACCELERATED MOTION

MATERIALS:

- lab sheet and writing utensil
- calculator
- spreadsheet and graphing software
- string
- 20 **g** mass with hook
- “frictionless” track + cart
- motion sensor + computer with sensor control and analysis software (self-tracking motion cart optional).

PREPARATION

Before we begin creating and testing a hypothesis regarding forces and motion, we need to familiarize ourselves with basic motion concepts and the equipment we will use to measure motion.

First set up the motion sensor and analysis program so that it displays the position, velocity, and acceleration vs. time graphs of your motion as you move in front of the sensor.

Next, create each of the following graphs by moving in front of the motion sensor. Have your instructor sign off on each graph as you progress.

Outcome 7-3

Constant Position

Create a constant position graph. Instructor signature:____________

Describe how you had to move to create this graph.

Describe the velocity and acceleration graphs created by your motion.

Constant Velocity

Create a constant velocity graph. Instructor signature:____________

Describe how you had to move to create this graph.

Describe the position and acceleration graphs created by your motion.

Constant Acceleration

Create a constant acceleration graph. Instructor signature:____________

Describe how you had to move to create this graph.

Describe the position and velocity graphs created by your motion.

ACCELERATED MOTION

Outcome 7-4

Now we will use the cart and track to test a hypothesis about how position, velocity, acceleration and net force are related. Setup the cart and track and motion sensor (or the self-tracking cart) to measure the position, velocity, and acceleration of the cart as it moves down the track.

Observation

So far we have been working only in situations when all forces were balanced, so the net force was zero.

Questions

What happens when there us only one unbalanced force so the net force is not zero?

Search Existing Knowledge

Search for answers to the previous questions. Write down what you find and be sure to cite your sources.

Qualitative Hypotheses

Provide a qualitative hypothesis about what will happen when the net force on an object is not zero.

Test

We will start by applying a single unbalanced force to an object. The object will be a cart. The cart will run on a smooth track to minimize friction. We will use a fan attached to the cart to cause a constant force on the cart. Without the fan running, the cart should stay in static equilibrium. Place the cart on the track and let go. Does the cart start rolling? If so, then there must have been an unbalanced force on the cart, even though the fan was off, so the track is probably not level. Level your track.

Analyze

Now turn on the fan and measure the velocity and acceleration of the cart.

What happens to the cart when the fan is running? Was the velocity constant or changing?

If the velocity was changing, record the acceleration here: _________
Record the standard deviation in the acceleration here:_____________

Conclusion

Does the result of your test agree with your qualitative hypothesis? Explain.

VERIFICATION OF NEWTON'S SECOND LAW

Outcome 7-4

During your search of existing knowledge you likely came across Newton's Second Law, which tells us how net force, mass, and motion are related. Look up and write down Newton's Second Law:

Test

Newton's Second Law has been well established, but to help us understand the law we want to re-test Newton's Second Law.

Measure the combined mass of the cart and fan and record here:__________

Use your previously measured acceleration, the cart mass, and Newton's 2nd Law to calculate the expected force provided by your fan:

Repeat the acceleration measurement for four additional cart masses (change the cart mass by adding accessory masses). Record all results, including standard deviations for the accelerations, in a chart below. Leave an extra empty column at the end.

Analyze

Use the fan force you calculated in the first trial to calculate what the accelerations should have been for each of the four additional trials. You may use a spreadsheet. Record your results in the empty column of the previous chart.

Did Newton's Second Law allow you to correctly predict the accelerations of your cart within the uncertainty in the acceleration measurement? Explain.

Double Check Assumptions

Let's double check our assumption that friction (or other forces) are not affecting our results. If our assumption that air resistance is negligible is valid, then these forces should be much smaller than the force provided by the fan. With the fan off, give the cart a gentle push and measuring the acceleration as the cart slows down due to air resistance and friction. Record the average acceleration of the cart during slow-down here:

Use the mass of the cart and Newton's Second Law to calculate the force on the cart due to air resistance and friction.

Conclusion

Do you think that friction and air resistance had a large effect on your test of Newton's Second Law? Explain by comparing the size of those forces to the fan force.

Did your test of Newton's Second Law provide evidence in support of Newton's Second Law? Whether the answer is yes, no, or inconclusive, be sure to explain how you arrived at that decision.

CHAPTER 105.

UNIT 8 LAB: COLLISIONS

COLLISIONS

Materials:

- lab sheet and writing utensil
- calculator
- spreadsheet and graphing software
- Low friction tracks + 2 carts
- Sensors and software for measuring velocity of at least one of the carts

Observation

We build crumple zones into cars, even though it means that cars are more easily "totaled" during collisions.

Question

Why do we use crumple zones even though it means that cars are more easily "totaled" during collisions?

Search Existing Knowledge

Search for answers to your question, explain/summarize what you learned, and cite your sources.

Hypothesis

Provide a hypothesis about whether bouncy elastic collisions or sticky inelastic collisions will create greater forces on a cart during a collision with another cart.

Test I

Use the velcro bumpers on the carts (or clay) so that they stick together when colliding. Measure the velocity of a cart while it collides into another cart that was stationary. You may use the accessory masses to adjust the masses of the carts however you prefer.

Record the initial velocity of the first moving cart here:___________

Record the final velocity of the two carts here:_______

Measure the mass of the first cart and record here:_________

Record the length of the collision (the time on your velocity graph during which the velocity of the cart was abruptly changing).

Analysis I

Calculate the initial momentum of the first cart:

Calculate the final momentum of the first cart:

Calculate change in momentum of the first cart:

Use the impulse-momentum theorem and your recorded collision time to calculate the average force on the first cart:

Test II

Now we will use the magnetic bumpers (or rubber bumpers) on the carts so that they bounce when colliding. Measure the velocity of a cart while it collides into another cart that was stationary. You may use the accessory masses to adjust the masses of the carts however you prefer.

Record the initial velocity of the first moving cart here:___________

Record the final velocity of the first cart here:_______

Measure the mass of first cart and record here:________

Record the length of the collision (the time on your velocity graph during which the velocity of the cart was abruptly changing).

Analysis II

Calculate the initial momentum of the first cart:

Calculate the final momentum of the first cart:

Calculate the change in momentum of the first cart:

Use the impulse-momentum theorem and your recorded collision time to calculate the average force on the first cart:

Conclusions

Which type of collision caused a greater force on the first cart?

Explain why this type of collision causes a greater force on the cart, in terms of what you learned in this lab.

CHAPTER 106.

UNIT 9 LAB: ENERGY IN EXPLOSIONS

SIMULATED EXPLOSION

Materials:

- lab sheet and writing utensil
- calculator
- "frictionless" track + two carts with spring-loaded bumper
- two motion sensors + computer with sensor control and analysis software (or one motion sensor and one self-tracking motion cart).

Outcome 9-1

Explosions

During an explosion, such as that which occurs within the cylinders of internal combustion engines, ________________________energy is converted into ____________________energy and _________________________energy.

Observation

Typically, after an explosion things are moving even though nothing was moving before the explosion.

Outcome 9-2

Questions

Do explosions conserve kinetic energy?
Do explosions conserve momentum?

Search Existing Knowledge

Find information about whether or not momentum and kinetic energy are each conserved during an explosion. Cite your sources.

Hypotheses

We will simulate an explosion by releasing a spring that was compressed between the two objects, causing them to separate. This produces the same situation an explosion, specifically that things are moving afterward, even when nothing was moving initially. Form two hypotheses, one regarding conservation of momentum and conservation of kinetic energy during the simulated explosion. As part of your hypotheses, draw diagrams of this situation before and after the "explosion" occurs.

Test

Place the two carts together with the loaded spring in the first cart facing the second cart. Record the motion of both carts while pushing the spring release button. Use a ruler to tap the button from directly above, making sure not to put any horizontal force on the button/cart.

Use your velocity data to determine the velocity of each cart immediately after the explosion has finished, but before the carts begin to slow down due to friction. Be sure to consider that the velocities should have opposite directions, but that your motion sensors will not necessarily record the correct directions. You will need to choose a positive and negative direction for your experiment and correct the directions recorded by your sensors accordingly. Record your final velocities for each cart below.

Measure the mass of each cart and record below:

Momentum Analysis

What was the total momentum of the system before the "explosion?"

Calculate the total momentum after the explosion.

Momentum Conclusions

Does your experiment support or refute your hypothesis on momentum conservation?

Kinetic Energy Analysis

What was the kinetic energy of the system before the explosion?

Calculate the total kinetic energy after the explosion.

Kinetic Energy Conclusion

Was kinetic energy conserved in this explosion?

Does your result support or refute your hypothesis?

If kinetic energy was not conserved in this experiment, did it increase or decreases?

What type of energy was converted into kinetic energy during this experiment?

Outcome 9-3

Efficiency Analysis

Let's find out the efficiency of this "explosion" at converting elastic potential energy into kinetic energy. First we need to know how much elastic potential energy was contained in the spring and to calculate that we need to know the spring constant and compression distance.

Measure the compression distance with a ruler and record here:

Use a force probe to measure the force required to compress the spring to half of the compression distance. Record the distance and force here:

Calculate the spring constant of the spring.

Calculate the elastic potential energy stored in spring when fully compressed.

Calculate the efficiency of the “explosion” at converting spring potential energy into elastic potential energy.

If the efficiency was not 100%, why not? Where did the missing mechanical energy go?

How much energy was not converted to kinetic energy?
Outcome 9-4

Power Output

Use tour velocity data to determine the length of time over which the elastic potential energy was converted to kinetic energy. Record here:__________

Use the time interval you found and the final kinetic energy of the carts to calculate the kinetic power output of the spring during the explosion.

Use the time interval you found to calculate the thermal power output of the spring during the explosion.

CHAPTER 107.

UNIT 10 LAB: MECHANISMS OF HEAT TRANSFER

COOLING IN A CUP

Materials:

- foam cups (8 **oz**)
- plastic or paper cups (8 **oz**)
- Aluminum foil
- Hot water (80-99) **°C**
- syringe or graduated cylinder
- thermometer or digital temperature sensor + computer with sensor control and analysis software

Observation

We observe that the cooling of hot liquid in a cup is affected by the cup material (foam, paper, plastic, metal) and by using a lid.

Question

Which raises the question: Among a metal lining, an insulating cup material, or a lid, which features are most important to keeping a hot beverage from cooling too quickly?

Search Existing Knowledge

Find information about how different mechanisms of heat transfer would be affected by using a lid and various combinations of materials. Record what you learn below.

Hypotheses

Use the information you found above to fill in the blank for each hypothesis below.

Starting with a plastic cup as our baseline, If ______________ does not contribute much heat loss, then changing to a foam cup will not significantly decrease the cooling rate.

If ______________ does not contribute much heat loss, then adding a lid to the foam cup will not significantly decrease the cooling rate.

If ______________ does not contribute much heat loss, then adding a foil lining to the foam cup and lid will not significantly decrease the cooling rate.

Test

We will test the rate at which a liquid cools in each of the situations above.

We will use the following procedure to control for the amount of water used in each test well as for possible differences temperature of the water and the room:

1. Set up a thermometer to continuously measure the room temperature.
2. Use a high precision instrument, such as a syringe or graduated cylinder, to measure the water volume for each test. Measure out enough hot water to fill the plastic cup about 1/2 way.
3. Place a thermometer in the water and wait ten seconds.
4. Start a timer and record the temperature of the room and the water simultaneously, leave the thermometers in place.
5. Calculate the initial difference between the water temperature and the room temperature.
6. Calculate half of the initial temperature difference.
7. Calculate the temperature the water will be when the temperature difference has dropped to half of its initial value.
8. Record the time when water temperature reached the value you calculated in the previous step. This is the half-life of the temperature difference.
9. Repeat the experiment to determine the half-life when foam cup is used.
10. Repeat the experiment to determine the half-life when a lid is used on the foam cup.
11. Repeat the experiment to determine the half-life when a foil lining is added to the foam cup and lid.

Analysis

Compared to the plastic cup, by what factor did changing to a foam cup increase the half-life of the temperature difference?

Compared to the foam cup, by what factor did adding a lid increase the half-life of the temperature difference?

Compared to the foam with a lid, by what factor did adding foil lining increase the half-life of the temperature difference?

Which feature increased the half-life by the largest factor?

Which feature decreased the half-life by the largest factor?

Conclusions

Which feature is most important to preventing hot liquids from cooling: quality insulation, metal lining, or lid? Explain.

Does radiation contribute much heat loss to hot water in a cup?

Does conduction contribute much heat loss to hot water in a cup?

Do convection and evaporation contribute much heat loss to hot water in a cup?

PART XII.

DESIGN-BUILD-TEST PROJECTS

Design-Build-Test projects give students hands-on experience with scientific concepts and the scientific process in general. The projects were originally designed to be tackled over the course of three one-hour lectures and one three-hour our lab, or roughly one week of instructional time. Providing intermediate feedback during various phases of the project improves student outcomes. For example, you might break the projects into phases such as: problem introduction and initial design phase (1 hour), a building, testing, and re-design phase (3 hours), and a re-build and final touches phase (1 hour).

CHAPTER 108.

SCALE BIOPHYSICAL DEAD-LIFT MODEL

PROJECT GOALS

- Use hands-on experience to reinforce physics concepts covered so far
- Jump cognition levels to *create*
- Practice critical thinking and the scientific process
- Have fun
- Assess Learner Outcomes: 2-2,2-3,2-4, 5-2

PROJECT DESCRIPTION

BACKGROUND

Lifting with your legs

The old saying "lift with your legs and not with your back" may be a bit vague, but the advice is sound from a biomechanics standpoint. Watch this video of Power-lifting world champion and world record holder Natalie Hanson perform a dead-lift at the 2017 IPF Open World Championships. Notice that Natalie seriously engages her leg muscles during the dead-lift.

Lifting with your back

This project will model the upper half of the body as a lever to estimate the forces applied to lumbar vertebrae when a person attempts to "lift with their back," meaning they bend at the waist instead of squat with their legs. That looks more like this:

This method moves the center of gravity of the upper body (and the weight to be lifted) farther out from rotation point, which causes more torque. Greater muscular force to is required to counter that torque, which in turn amplifies the forces on the spine. When done correctly and with appropriate weight, this type of lift can be useful in strengthening the hamstrings, glutes, and back, but generally speaking this lifting technique should be avoided in favor of lifting with the legs for both work and play.

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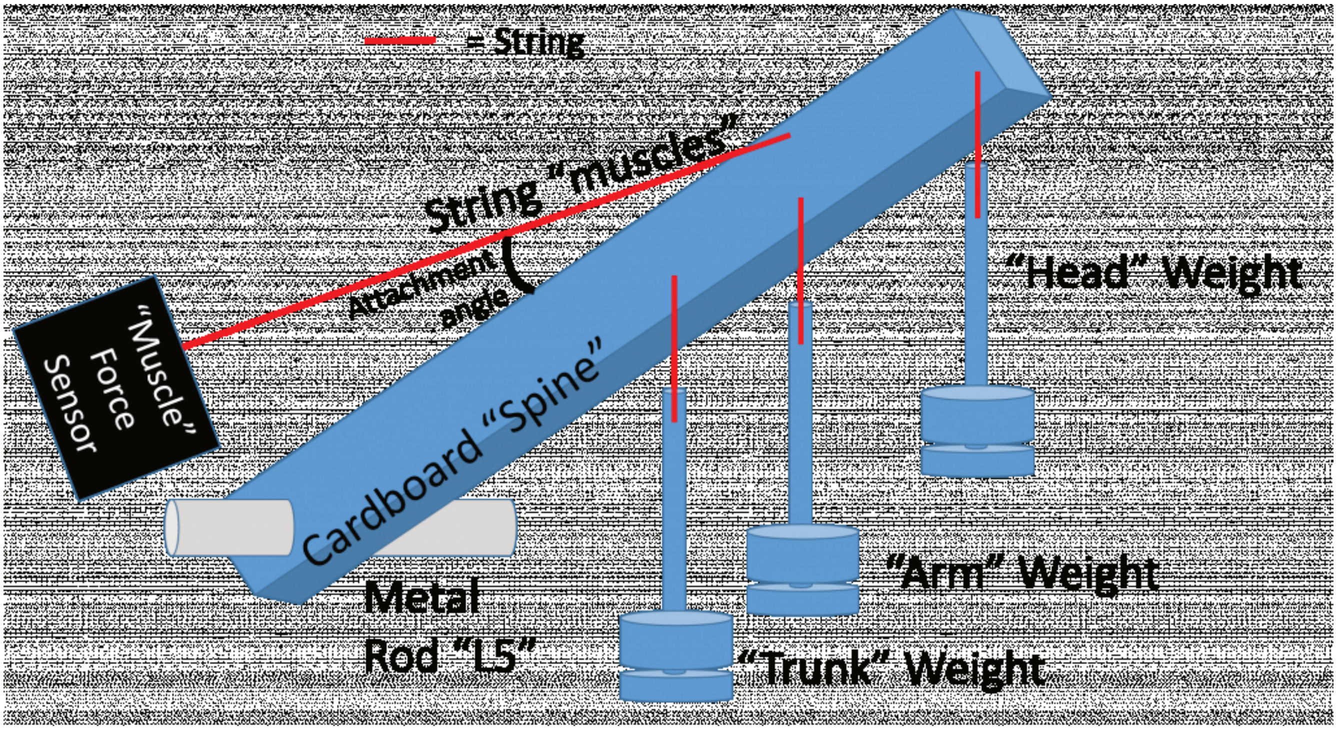


Diagram of a model of the spine while lifting with the back.

1. You will create a scale model of lifting with your back. The spine will be made from cardboard that will be provided.
2. The primary rotation point when lifting with your back is the fifth lumbar vertebrae (L5). You will be provided a medal rod to serve as this rotation point.
3. You will use provided string to serve as the erector spinae muscles that lift the back and use a force sensor to measure the tension in the string.
4. You will use provided protractor to maintain the attachment angle of the erector spinae muscles during each force measurement.
5. Your model will incorporate the scaled weight of the head, torso, and arms, located at the correct scaled distances from L5.
   - For an average body the distances from L5 to the center of gravity for each body part are:
     - 0.36 **m** to the trunk
     - 0.48 **m** to the arms (this is also the attachment distance point for the erector spinae muscles).
     - 0.72 **m** to the head
   - You will need to set the scale of your model to match the length of your cardboard. It should be something similar to 3:1.
   - The weights of each body section, as a fraction of body weight are:

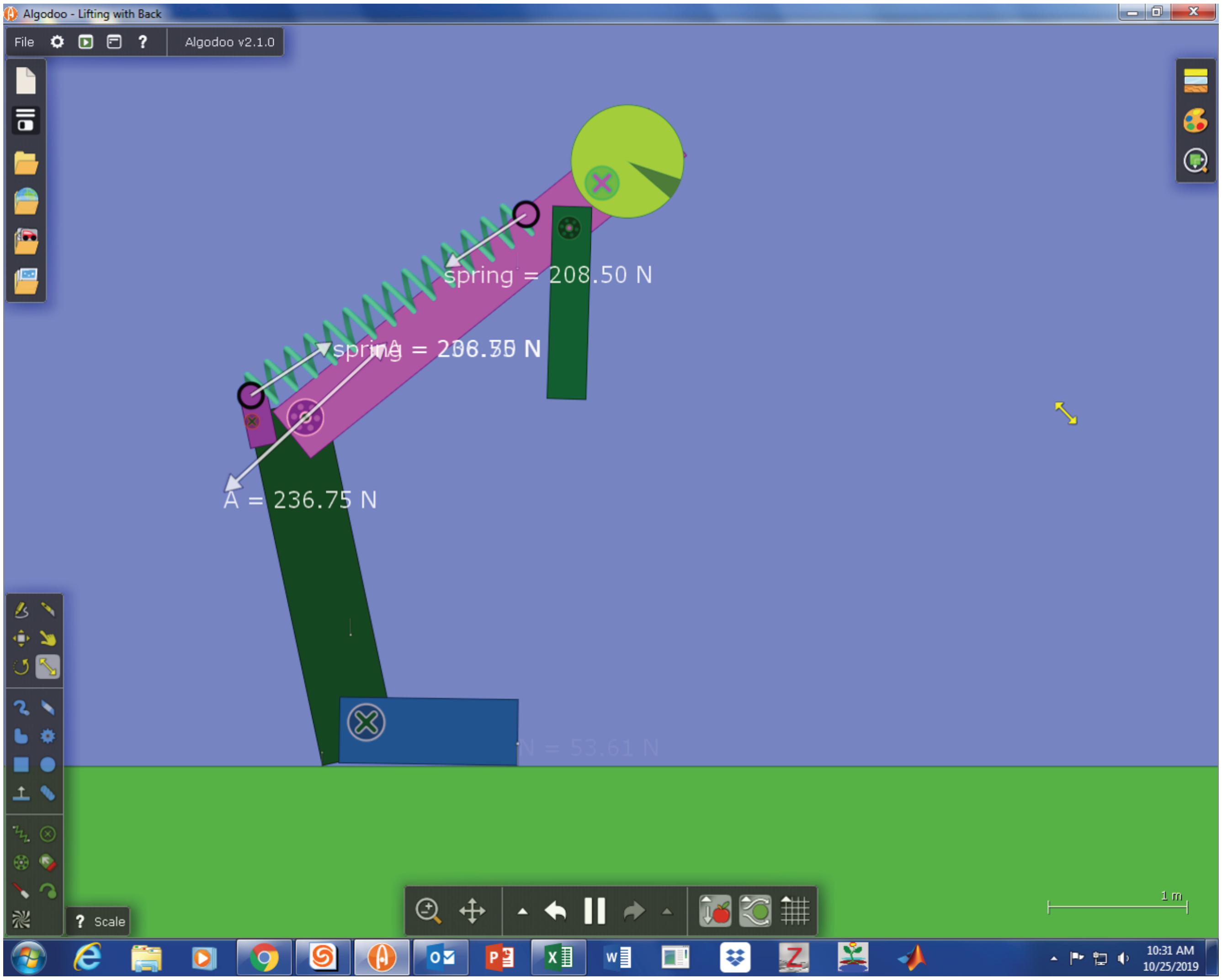
- Head is 0.7 of total body weight
- Two Arms are 0.12 of total body weight
- Trunk is 0.46 of total body weight

◦ You will need calculate the weights based on your choice of human body to model and then scale them accordingly. I suggest something like 20:1 for the weights to ensure you don't overwhelm the force sensor (make sure the sensor set to ± 50 **N**).

6. Re-scale your force measurements to predict the actual tension in actual human erector spinae muscles.
7. We will work together as a class to calculate the compressive and shear forces on the spine at each angle. You are not responsible for this in your report.

COMPUTER MODEL PROJECT DETAILS

Alternative to the scale model, you may use the free program Algodoo to create a computer model of the human body. The program allows you to attach objects together, control the object properties like size, mass and density, and then the program applies mathematical models based physics concepts in order to predict the forces experienced by the objects and how they will move in response. To build your model you will follow all of the same steps as for the scale model, except that your model will be built in the program, the size and weights of the objects will be the same as for your human body (not scaled) and the force values will be provided by the program (instead of a force sensor). The image below shows an example of such a model, but the example is not to scale.



Screen capture of a model of a person bending over created in the Algodoo program

PROJECT ASSESSMENT AND GRADING

Whether you created a scale model or a computer model, your project will assess the concepts listed below and your project grade will be determined according to the criteria and points listed under each concept. Use this as a checklist to make sure you have completed all parts of the project.

1. ***Unit Conversion*****:** The model is correctly scaled to the human body you chose to model.
    - Diagram lengths are correct (to scale) = 1pt
    - Model lengths are correct (to scale) =1pt
    - The body section weights are correct based on the body-weight fractions provided in the Project Details Section (scaled to the human body you have chosen to model) = 1pt
    - The body part weights are placed at the correct locations on your model spine based on the distances provided (to scale) = 1pt

2. ***Levers:*** The model allows you to measure the forces needed to answer your question.
   - Your model spine articulates a full 90° = 1pt
   - The 12° attachment angle of the erector spinae muscles remains constant throughout your measurements =1pt
   - The "muscular force" measured with your force probe is measured at 5° intervals from 0° to 90° = 2pt
3. ***Strength of Materials***: The model materials do not fracture, rupture, tip over, or otherwise fail under the scale load.(The axle of the scale model may be clamped down).
   - No failure, tip, fracture or rupture = 1pt
4. ***Scientific Method*****:** Process is well documented in a typed project report with the sections listed in bold below
   - **Question**
     - Statement of the question we are trying to answer with our model = 1pt
   - **Assumptions**
     - List of assumptions needed to make your model applicable = 2pt
   - **Build**
     - Neat documentation of problems encountered during build = 2pt
     - Neat documentation of solutions to build issues and changes to design = 2pt
   - **Initial Testing**
     - Neat documentation of problems encountered during initial testing of design =2pt
   - **Redesign**
     - Neat documentation of solutions to testing problems and resulting changes to design = 2pt
     - Neat final updated scale diagram = 1pt
   - **Analysis**
     - Neat documentation of results of final testing, including force values and angle values = 2pt
     - Spreadsheet with angle and force data entered and labeled with units= 2pt
     - A column that correctly calculates the full-scale human tension from your measurement values.
     - Appropriately labeled graph of Muscle Force vs. Angle = 2pt
     - The maximum force and angle at which it occurs is identified. = 2pt

        - Estimates of the uncertainty in measurements of angles and forces= 2pt
    - **Conclusions**
        - Explanation of whether the forces predicted by the model are of the right order of magnitude, with supporting evidence = 1pt
        - Explanation of specific steps that could be taken to improve the mode = 1pt

ADDITIONAL INFORMATION TO CONSIDER

- You may use any resource you like for guidance, however only students in you group may work on your model or add to the documentation AND ***you must cite your sources in your project report***. You can use these citation guides if you like:
    - For public domain and CC licenses
    - For other sources (APA Style)
- You do not have to generate your diagrams on the computer unless you want to. You can draw them by hand and attach them to your report as long as they are still neat, well labeled, properly scaled, and the dimensions are indicated.
- Your project will receive a group score, however students not actively participating and contributing will not receive credit for the project.
- You will be able to go through as many rounds of design/build/test as you would like within the time allotted for this project.
- All projects must have their final evaluation on or before the last day of the period allotted for the project.
- Don't hesitate to ask your instructor for help or ask clarification question regarding the project expectations. Asking early is better than asking late.

CHAPTER 109.

BIOPHYSICAL MODEL OF THE ARM

PROJECT GOALS

- Use hands-on experience to reinforce physics concepts covered so far
- Jump cognition levels to *create*
- Practice critical thinking and the scientific process
- Have fun

PROJECT DESCRIPTION

Build a scale articulating model of the human arm from the shoulder to the wrist. The model will include the lower arm, upper arm, elbow joint, biceps and triceps muscles and associated tendons. The model will be made out of cardboard, glue, twist ties and wooden dowels. The articulation of muscles will be done using syringes and tubing to form hydraulic actuators and twist ties will serve as tendons in similar fashion to the process seen in the following video:

Your project assess the concepts listed below and your project grade will be determined according to the criteria listed under each concept. The project is worth 15 points overall, and the distribution of points among the criteria are listed under each concept.

1. Scientific Method: Creation process is well documented in a typed project report with the sections listed in bold below:
    - **DESIGN**
    - Neat documentation of design considerations and how they relate to concepts covered in class = 1pt
    - Neat scale diagram of your design before building begins. Must include labels and dimensions. = 1pt
    - **BUILD**
    - Neat documentation of issues encountered during build = 1pt
    - Neat documentation of solutions to build issues and changes to design = 1pt
    - **TEST**

    - Neat documentation of issues encountered during testing of design =1pt
    - **REDESIGN**
    - Neat documentation of solutions to testing issues and changes to design = 1pt
    - Neat final updated scale diagram = 1pt
2. Unit Conversion: The model is a 2:3 scale size of a human arm.
    - Scaled 2:3 = 2pts
    - Proportionally scaled, but not 2:3 = 1pt
3. Forces and Torques: The model is capable of curling at least 1:100 the weight that a human arm can curl.
    - Curls at least 1:100 scale weight = 2 pts
    - Curls weight, but not 1:100 scale weight = 1pt
4. Levers: The model actuates with the same range of motion (in terms of elbow angle) as the human arm.

A YouTube element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=1580

- Articulates full human range of motion = 2 pts
- Articulates, but not full human range of motion= 1pt

5. Stability: The model does not tip over under the 1:100 scale load.
   - Remains standing = 1pt
6. Strength of Materials: The model materials do not fracture, rupture, or otherwise fail under the 1:100 load.
   - No failure, fracture or rupture = 1pt

Additional Information to Consider:

- You may use any resource you like for guidance, however only students in you group may work on your model or add to the documentation AND ***you must cite your sources in your project report***.
- You don't have to build the control levers, you can just hold and operate your two control syringes.
- Your model does not need to rotate like the one in the example video.
- Do not build a hand, we will hang a weight from the end of your model's forearm for the testing phase.
- You do not have to generate your diagrams on the computer unless you want to. You can draw them by hand and attach them to your report as long as they are still neat, well labeled, properly scaled, and the dimensions are indicated.
- Your project will receive a group score, however students not actively participating and contributing will not receive credit for the project.
- You will be able to go through as many rounds of design/build/test as you would like within the time allotted for this project.
- All projects must have their final evaluation on or before the last day of the period allotted for the project.
- Don't hesitate to ask your instructor for help or ask clarification question regarding the project expectations.

CHAPTER 110.

MARS LANDER

PROJECT GOALS

- Use hands-on experience to reinforce physics concepts covered so far
- Jump cognition levels to *create*
- Practice critical thinking and the scientific process
- Have fun

PROJECT DESCRIPTION

LANDER DELIVERY

Welcome to the first briefing for the touchdown redundancy team. Please play close attention because I am going to throw a lot of information at you.

Now, as you are aware the sky crane has emerged as the most practical method of delivering relatively massive payloads to the Martian surface. For a brief recap of that system watch the following video:

As we know, the sky crane system successfully delivered the curiosity rover to Mars, an important step in getting this historic point, where we are now in mission design phase for the Human Exploration of Mars. Several sky crane systems will be used to deliver supplies, equipment and the return rocket ahead of the human mission.

YOUR TASK

We calculate a low failure probability for the sky crane, but we also estimate that the large majority of that probability is concentrated during the time when the crane is within 14 **m** of the surface.

We know humans and equipment can only survive forces up to a certain threshold. Therefore, this team will design a lander which will prevent accelerations above the safety threshold for drops up to 14 **m** on Mars. This will ensure that the humans and critical equipment survive an unexpected drop to the Martian surface with no adverse effects.

The system you design to accomplish this must not rely on any other system, which would create a redundancy spiral, and that includes any electronics systems. (Therefore a parachute deployment system is not acceptable).The system must be built into the structure of the lander itself. You will be designing a Mechanical Acceleration Suppression System, or M.A.S.S.

DESIGN AND TESTING PARAMETERS:

In order to generate a diversity of design ideas the team will be split into groups. I want hands-on contributions from all members, so groups cannot be bigger than three. I also want us checking and double-checking each other's work, so no groups smaller than two.

Each group will design a system, build a model, and we will test them in our free-fall facility here in the building. The model test subjects and equipment we will use will be three raw eggs.

We must recognize that *g* on mars is only about 3.8 **m/s/s** compared to 9.8 **m/s/s** on Earth so you will calculate a new drop height for testing our models here on Earth.

The model lander must fall straight down from the calculated height and land within a 25 **cm** x 25 **cm** area to ensure that it lands in the safe location identified by the sky crane imaging system. (Therefore a parachute system is not acceptable).

Due to the fuel requirements and cost of launching mass into space, you are limited to a total mass of 500 **g** for your model lander system, including the payload (eggs).

Due to the size limitations of the spacecraft you are limited to a total size of 20 **cm** wide x 20 **cm** long by 30 **cm** high for your model lander system.

You are also limited on your design budget. In order to maximize the efficiency of taxpayer dollars for space exploration you are limited to the following materials, with associated costs and your total cost cannot go above 500 **USD.**

Glue: No cost

A YouTube element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/bodyphysics/?p=3349

Paper: 4 **USD/gram**
Cardboard: 6 **USD/gram**
Wood (Popsicle sticks) 10 **USD/gram**
Aluminum Foil: 25 **USD/gram**

PRESENTATION AND TESTING:

You will give the class an **8 minute** presentation on your model that will include the following sections:

1. Model design features
2. Physics concepts and reasoning behind your design
3. Materials cost breakdown for your model
4. Difficulties and solutions/redesigns during your project

MODEL EVALUATION (GRADING)

C-grades will be earned by:

1. correctly completing and submitting the guide calculations worksheet
2. fully participating in the design-build process
3. keeping your design within budget limitations
4. contributing to your group presentation.

B-Grades will be earned by doing the above plus:

1. landing completely within the designated area
2. preventing damage to the test subject (egg).

A-Grades will be earned by doing all of the above plus:

1. keeping within mass and size limitations

GUIDE CALCULATIONS:

DROP HEIGHT, SPEED, AND ACCELERATION

Using our knowledge of conservation of mechanical energy determine the Earth drop height we need to provide the same impact speed as a 14 **m** drop on Mars:

We want to limit the peak acceleration felt by the cargo to 10 **g**. The humans and equipment will be strapped tightly to the lander frame so the lander frame must not accelerate at more than 10 **g**. What is this acceleration in m/s/s?

IMPACT FORCE

Assuming your lander + payload have the maximum 300 **g** mas, calculate the maximum net force that can be applied to the lander on touchdown without exceeding the threshold acceleration:

Draw a free body diagram of the lander during impact

Determine the peak normal force that can be applied to your model by the ground in order to prevent such an acceleration. This is your safety threshold force.

You may use force plate to test version of your models and see how they react to forces of various sizes.

IMPACT DURATION

Use the lander mass and impact speed to calculate the change in momentum of the lander upon impact.

If you design your lander to keep the average net force applied on impact to be less than 1/3 of the safety threshold, then the peak force will likely not exceed the safety threshold. Draw a F vs. t curve for the impact that illustrates this idea.

If you were to achieve this average force value of 1/3 the peak force threshold, then over what time would you need to spread the impact?

What design features will you implement to spread out the impact duration?

TESTING

Record the dimensions of your lander here:

Width:________Length:______Height:________

Record the mass of the lander here:________

Record the masses and total cost of various materials used:

Record the total cost of your lander here:______

Did your payload survive without damage?

GLOSSARY

1st Law of Thermodynamics

Any change in the internal energy of a system must in the process of exchanging heat, doing work, or both.

3rd class lever

a lever with the effort between the load and the fulcrum.

absolute zero

A lower limit of temperature corresponding to the minimum possible average kinetic energy of atoms and molecules.

acceleration

the change in velocity per unit time, the slope of a velocity vs. time graph

acceleration due to gravity

the rate at which an object changes velocity when gravity is the only force acting on the object

accelerations
accurate

refers to the closeness of a measured value to a standard or known value

Achilles tendon

a tough band of fibrous tissue that connects the calf muscles to the heel bone

air resistance

a force acting opposite to the relative motion of any object moving with respect to a surrounding fluid

analyze

examine methodically and in detail the constitution or structure of information for purposes of explanation and interpretation

anisotropic

having a physical property that has a different value when measured in different directions

apparent weigh
apparent weight

the reading on a scale that is used to measure the weight of an object that is submerged in a fluid

approximation

a rough value obtained without making a measurement by using prior knowledge and assumptions.

Archimedes' Principle

The upward buoyant force that is exerted on a body immersed in a fluid, whether fully or partially submerged, is equal to the weight of the fluid being displaced by the body

assumption

ignoring some compilation of the in order to simplify the analysis or proceed even though information is lacking

at rest

not moving

atmospheric pressure

the pressure exerted by the gasses in the atmosphere

average acceleration

average change in velocity per unit time, calculated as change in velocity during a time interval divided by the time interval

average speed

average rate at which distance was traversed, equal to total distance traveled within a time interval, divided by the time interval

average velocity

the average of all instantaneous velocities that occurred within a certain time interval, equal to the displacement divided by the time interval

Barriers

Objects, events, or conditions that hinder access.

bedrock

hard rock exposed or buried at the earth's surface

biased

prejudice in favor of or against one thing, person, or group compared with another, usually in a way considered to be unfair or inaccurate.

bipedal

(of an animal) using only two legs for walking

black body emitter

an ideal object which absorbs all radiation that strikes it, with no reflection, and releases that energy as thermal radiation in a way that depends only on its temperature

Bloom's Taxonomy
Bloom’s Taxonomy

A framework for categorizing educational goals.

Blooms Taxonomy
BMI

Body Mass Index (BMI) is a person’s weight in kilograms divided by the square of height in meters. BMI can be used to screen for weight categories that may lead to health problems but it is not diagnostic of the body fatness or health of an individual

brittle

liable to break or shatter due to relatively inability to deform under stress (not ductile)

buoyant force
buoyant force

the upward force exerted by any fluid upon a body placed in it

calibrated

defining the values of an instrument's readings by comparison to a standard

calories

unit of energy equivalent to 4.184 Joules

cantilevered

any rigid structure projecting from a support, especially one in which the projection is great in relation to the depth of the structure

cardiovascular system

heart, blood and blood vessels

Carnot efficiency

the maximum theoretical efficiency that a heat engine could achieve when operating between two set temperatures, as permitted by the Second Law of Thermodynamics

Celsius

the most common relative temperature scale

center of gravity

a point at which the force of gravity on body or system (weight) may be considered to act. In uniform gravity it is the same as the center of mass.

center of mass

a point representing the mean (average) position of the matter in a body or system

centripetal acceleration

component of the acceleration directed toward the center of a circular motion

centripetal force

a name given to the component of the net force acting perpendicular to an objects motion and causing to take a circular path

chain-link method

a specific method for unit conversion that is designed to aid in reducing mistakes.

change of phase

the change of a substance between states of being solid, liquid, or gas (or other more exotic phases)

chemical potential energy

energy stored in the chemical bonds of a substance

class of lever
coefficient of friction
coefficient of restitution

the fraction of relative velocity remaining after a collision, for collision with a stationary object equal to the ratio of final speed to initial speed

Cognition

The mental action or process of acquiring knowledge and understanding through thought, experience, and the senses

combustion

the process of burning, the rapid chemical combination of a substance with oxygen, involving the production of heat and light

compression

reduction in size caused by application of compressive forces (opposing forces applied inward to the object).

Computer modeling

using a computer program that is designed to simulate what might or what did happen in a situation

concentration

relative amount of one substance or quantity contained or stored within another substance or quantity, such as thermal energy per molecule

conclusion

a judgment or decision reached by reasoning and logic based on results provided by analysis of data

condensation

Process of vapor changing phase into a liquid.

conduction

the process by which heat or directly transmitted through a substance when there is a difference of temperature between adjoining regions, without movement of the material

conservative forces

forces that do work which converts energy between forms of mechanical energy (potential energy and kinetic energy)

conservative work

work that converts energy between mechanical forms of energy (potential energy and kinetic energy)

conserved

a physical quantity is said to be conserved when its total value does not change

constant

not changing, having the same value within a specified interval of time, space, or other physical variable

convection cell

cyclic fluid flow caused by natural convection

conversion factor

a number that relates two different units of measure for the same quantity and allows conversion between the two units

Coriolis Effect

an effect whereby a mass moving in a rotating system behaves as though experiencing a force (the Coriolis force) that acts perpendicular to the direction of motion. On the earth, the effect tends to deflect moving objects to the right in the northern hemisphere and to the left in the southern and is important in the formation of cyclonic weather systems

cross sectional area
cross-sectional area

The cross-sectional area is the area of a two-dimensional shape that is obtained when a three-dimensional object - such as a cylinder - is sliced perpendicular to some specified axis at a point. For example, the cross-section of a cylinder - when sliced parallel to its base - is a circle

crust

the relatively thin layer of rock that makes up the outermost solid shell of our planet

data

collection of values measured during an experiment

density

relation between the amount of a material and the space it takes up, calculated as mass divided by volume.

dependent variable

a factor, condition, or property that changes in response to purposeful changes in the independent variable

derivation

a sequence of steps, logical, mathematical, or computational, combining one or more results to obtain another result

dew

water that condenses on cool surfaces at night, when decreasing temperature forces humidity to 100% or higher

dispersion

the action or process of distributing a quantity over a wide space

displaced

pushed out of original position, typically in reference to fluid pushed out of the way by an object placed in the fluid, or an object being displaced from its equilibrium position

displacement

change in position, typically in reference to a change away from an equilibrium position or a change occurring over a specified time interval

displacement method

method for determining the volume of an object by measuring how much water it displaces

drag coefficient

a number characterizing the effect of object shape and orientation on the drag force, usually determined experimentally

drag force

a force applied by a fluid to any object moving with respect to the fluid, which acts opposite to the relative motion of the object relative to the fluid

ductile

able to be deformed without failure, pliable, not brittle

dynamic equilibrium

a state of being in motion, but having no net force, thus the motion is constant

efficiency

ratio of useful work performed to total energy expended

efficient
effort

referring to a lever system, the force applied in order to hold or lift the load

effort arm

in a lever, the distance from the line of action of the effort to the fulcrum or pivot

elastic collision

collision in which no permanent deformation occurs, and kinetic energy is conserved

Elastic Limit

the maximum stress that can be applied to a material before it leaves the linear region

elastic modulus

measures of resistance to being deformed elastically under applied stress, defined as the slope of the stress vs. strain curve in the elastic region

elastic potential energy

energy stored in the deformation of a material

elastic region

the range of values for stress and strain values over which a material returns to its original shape after deformation

Electromagnetic radiation

light waves, or coupled oscillating electric and magnetic fields fields that can travel through empty space and carry both energy and momentum without moving mass

electromagnetic spectrum

the range of wavelengths or frequencies over which electromagnetic radiation extends

emission spectrum

data which describes the relative amount of electromagnetic radiation emitted by an object across a range of wavelengths, or conversely frequencies.

emissivity

measure of a material's effectiveness at emitting energy as thermal radiation

Empirical models

mathematical explanation of the relation between measured values that is used for making predictions

Energy

A quantity representing the capacity of an object or system to do work.

Energy pathway

the process of transferring chemical potential energy stored in food to useful work and thermal energy

Entropy

A measure of energy dispersion in a system.

equilibrium

a state of having no unbalanced forces or torques

evaporation

vaporization that occurs on the surface of a liquid as it changes into the gas phase

exhaust heat

heat transferred to the environment rather than being used to do useful work

Fahrenheit

a relative temperature scale commonly used in the U.S.

Feedback

1) information about reactions to a product, a person's performance of a task, etc. which is used as a basis for improvement.
2) the modification or control of a process or system by its results or effects, e.g., in a biochemical pathway or behavioral response

final position

position at the end of the time interval over which motion is being analyzed

final velocity

the value of velocity at the end of the time interval over which motion is being analyzed

First class levers

levers with the fulcrum placed between the effort and load

First Law of Thermodynamics

the change in internal energy of a system is equal to the heat added to the system minus the work done by the system

force

any interaction that causes objects with mass to change speed and/or direction of motion, except when balanced by other forces. We experience forces as pushes and pulls.

force of gravity

attraction between two objects due to their mass as described by Newton's Universal Law of Gravitation

forced convection

transfer of heat due to the movement of fluid molecules driven by external factors other than thermal expansion.

form drag

that part of the drag on an object that arises from its shape and angle at which it moves the fluid and which can be decreased by streamlining

fracture

the separation of an object or material into two or more pieces under the action of stress and associated strain

free body diagram

a graphical illustration used to visualize the forces applied to an object

free body diagrams
free fall

the motion experienced by an object when gravity is the only force acting on the object.

frequency

the number of cycles or oscillations occurring per second, as in the frequency of the electromagnetic oscillations in a light wave

friction

a force that acts on surfaces in opposition to sliding motion between the surfaces

friction coefficient

coefficient describing the combined roughness of two surfaces and serving as the proportionality constant between friction force and normal force

fulcrum

the point on which a lever rests or is supported and on which it pivots

Glossary

The glossary feature includes rollover definition capability.

gravitational potential energy

potential energy stored in objects based on their relative position within a gravitational field

gravitational potential energy
gravity
gravity passes
Green House Gas Effect

Elevation of Earth's temperature relative to the atmosphere-free condition caused differential absorption of UV, visible, and IR light by specific gases and particles present in the atmosphere.

Heat

An amount of thermal energy transferred due to a difference in temperature.

heat capacity

The amount of energy required to raise the temperature of an object by one temperature unit.

Heat death

the degradation of energy quality associated with a spontaneous processes.

heat engines

devices for converting thermal energy to useful work and exhaust heat

heat index

a measure of how hot feels (according to difficult in exhausting heat) when relative humidity is factored in with the actual air temperature

heat loss rate

the amount of heat (thermal energy transferred due to a temperature difference) that leaves an object per unit time

heat transfer coefficient

a measure how well thermal energy is transferred as heat for a given temperature and contact area

histogram

A graph of relating how often a value falls within a certain range.

homeostasis

is the state of steady internal physical and chemical conditions maintained by living systems

Hooke's Law

the restoring force exerted by a spring is equal to the displacement multiplied by spring constant

horsepower

a unit for power equal to 746 Watts

hydrostatic weighing

a technique for measuring the mass per unit volume of a living person's body. It is a direct application of Archimedes' principle, that an object displaces its own volume of water

Hyperthermia

The condition of having a body temperature well above the normal range.

hypothermia

The condition of having a body temperature well below the normal range.

hypothesis

a proposed explanation made on the basis evidence that can be supported or refuted by the result of experimentation

impulse

the average force applied during a time interval multiplied by the time interval

impulse-momentum theorem

the change in momentum experienced by an object is equal to the net impulse applied to the object

independent variable

the factor, property, or condition that is purposefully changed within an experiment

inelastic collision

a collision for which kinetic energy is not conserved

inertia

the tenancy of an object to resist changes in motion

infrared

having a frequency just lower than visible red light but higher microwaves.

initial position

position at the start of the time interval over which motion is being analyzed

initial velocity

the value of velocity at the start of the time interval over which motion is being analyzed

instantaneous

existing or measured at a particular instant

internal energy

the total of a systems thermal energy and chemical potential energy, the total energy stored microscopically within the system

irreversible

a process that is not a reversible process in which the system and environment can be restored to exactly the same initial states that they were in before the process

Isolated system

a system for which neither thermal energy or particles are allowed to leave or enter.

isotropic

having a physical property which has the same value when measured in different directions

iterative

relating to or involving repetition of a mathematical or computational procedure applied to the result of a previous application

Joule

International standard (SI) unit of Energy

kelvin

SI unit of temperature

kinetic energy

energy which a body possesses by virtue of being in motion, energy stored by an object in motion

kinetic friction

a force that resists the sliding motion between two surfaces

Latent heat

the thermal energy required to change the phase of a substance (or released by the substance when it changes phase)

latent heat of fusion

the thermal energy required to melt a unit mass of a substance

latent heat of vaporization

Thermal energy input required to change a unit mass of liquid into vapor.

law

a statement, usually in the form of a mathematical equation, that summarizes, but not explains, the results of repeated experiments or observations that describe some aspect of the natural, usually within a certain range of application.

Law of Conservation of Energy

the net work on a system must be equal to the sum of the changes in kinetic, potential, and thermal energies

Law of Conservation of Momentum

the combined total momentum of all objects in system immediately prior to a collision be the same as the total momentum of all objects in the system immediately after the collision

Learning management system

a software application for the administration, documentation, tracking, reporting, and delivery of educational courses, training programs, or learning and development programs

lever

a rigid structure rotating on a pivot and acting on a load, used multiply the effect of an applied effort (force) or enhance the range of motion

lever arm

perpendicular distance between the line of action of a force causing a torque and the pivot about which the torque occurs

lever classes

There are three types or classes of levers, according to where the load and effort are located with respect to the fulcrum

line of action

an imaginary line that is parallel to a force and extends in both directions from the point of application of the force

linear region

region of the stress vs. strain curve for which stress is proportional to strain and the material follows Hooke's Law

linear thermal expansion coefficient

Material property that relates the fractional change in length experienced by an object due to a unit change in temperature.

load

a weight or other force being moved or held by a structure such as a lever

locomotion

movement or the ability to move from one place to another

longitudinal

running lengthwise rather than across

magnitude

the size or extent of a vector quantity, regardless of direction

malleable

able to be hammered or pressed permanently out of shape without breaking or cracking

mantle

the mantle is the mostly-solid bulk of Earth's interior. The mantle lies between Earth's dense, super-heated core and its thin outer layer, the crust.

mass

a measurement of the amount of matter in an object made by determining its resistance to changes in motion (inertial mass) or the force of gravity applied to it by another known mass from a known distance (gravitational mass). The gravitational mass and an inertial mass appear equal.

measurement error

Measurement Error (also called Observational Error) is the difference between a measured quantity and its true value. It includes random error (naturally occurring errors that are to be expected with any experiment) and systematic error (caused by a mis-calibrated instrument that affects all measurements)

measurement units

a unit of measurement is a definite magnitude of a quantity, defined and adopted by convention or by law, that is used as a standard for measurement of the same kind of quantity. Any other quantity of that kind can be expressed as a multiple of the unit of measurement.

mechanical advantage

ratio of the output and input forces of a machine

mechanical efficiency

the effectiveness of a machine in transforming the energy input to the device to mechanical energy output

mechanical energy

the sum of potential and kinetic energy

Melting

changing phase from solid to liquid.

Metacognition

awareness and understanding of one's own thought processes

metastable equilibrium

a state in which a slight disturbance results in a restoring force that maintains stability, but a sufficiently large disturbance moves the system into an unstable region (or different metastable region)

method of significant figures

using the number of digits provided in a measurement value to indicate the measurement uncertainty

metric prefix

a unit prefix that precedes a basic unit of measure to indicate a multiple or fraction of the unit

model

a representation of something that is often too difficult (or impossible) to observe or display directly

momentum

the combined effect of mass and velocity, defined as mass multiplied by velocity

Motion graphs

graphs or plots with time on the horizontal axis and position or velocity or acceleration on the vertical axis

Multitasking

Splitting attention between more than one task at a time.

Natural convection

Transfer of heat due to fluid movement caused by thermal expansion of the fluid

negligible

small enough as to not push the results of an analysis outside the desired level of accuracy

nervous system

the network of nerve cells and fibers which transmits nerve impulses between parts of the body

net force

the total amount of remaining unbalanced force on an object

net torque

remaining unbalanced torque on an object

net work

total work done on an object, equal to the addition of all separate works done on the object, or the work done by the net force

Newton

the SI unit of force. It is equal to the force that would give a mass of one kilogram an acceleration of one meter per second per second

Newton's 3rd Law
Newton's First Law

an object's motion will not change unless it experiences a net force

Newton's Law of Cooling

Observation that the rate of change of the temperature of an object is proportional to the difference between its own temperature and the environmental temperature

Newton's Second Law

the acceleration experienced by an object is equal to the net force on the object divided my the object's mass

Newton's Third Law

for every force applied by an object on a second object, a force equal in size, but opposite in direction, will be applied to the first object by the second object

Newtons
non-conservative forces

forces that do non-conservative work, which is work that does not transfer energy only among kinetic and potential forms (mechanical energy)

normal force

the outward force supplied by an object in response to being compressed from opposite directions, typically in reference to solid objects.

null hypothesis

default position that there is no relation between two measured quantities

numerical simulation

a calculation that is run on a computer following a program that implements a mathematical model for a physical system

order of magnitude

designating which power of 10 (e.g. 1,10,100,100)

order of magnitude estimation

the process of approximating a value to obtain a result you expect to at least be within one order of magnitude of the correct answer.

origin

location where the position is zero

oscillatory

repetitive variation, typically in time, of some measure about a central value

parallel

side by side, pointing in exactly the same direction, or having the same distance continuously between them

Pascals

the SI derived unit of pressure used to quantify internal pressure, stress, Young's modulus and ultimate tensile strength. It is defined as one newton per square meter

perfectly elastic collision

a collision for which initial and final values of the total kinetic energy of all objects in the system are the same

perfectly inelastic collisions

collisions in which the colliding objects stick together (explosions are perfectly inelastic collisions in reverse)

perpendicular

at an angle of 90° to a given line, plane, or surface

perpendicular distance
Physical models

mechanistic explanation of how a physical system works

piezoelectric effect

the ability of certain materials to generate an electric charge in response to applied mechanical stress

pivot

the central point, pin, or shaft on which a mechanism turns or oscillates

plastic region

the range of values for stress and strain over which a material experiences permanent deformation

position

location in space defined relative to a chosen origin, or location where the value of position is zero

potential energy

the energy stored within an object, due to the object's position, arrangement or state. Examples are gravitational potential energy due to the relative position of masses and elastic potential energy caused by being under stress

pounds

a unit of force equal to 4.44822 Newtons, or the the weight of a 0.4536 kg mass on Earth's surface

power

the rate at which work is done, the rate at which energy is converted from one form to another

precision

refers to the closeness of two or more measurements to each other

preponderance

the quality or fact of being greater in number, quantity, or importance

pressure

force per unit area

principle

principles summarize rules created and followed by scientists when formulating hypotheses, designing experiments, analyzing results.

Principle of Conservation of Energy

Energy cannot be created or destroyed, only transferred from one type to another and/or from one object to another

Principle of Conservation of Momentum

the momentum of an object or collection of objects (system) remains constant if the net impulse on the system is zero

prone

lying horizontally with the face and torso facing down

proportional

having a constant ratio to another quantity

qualitative

describing what happens, but not how much happens

quantitative

describing what and how much happens

radians
radians (rads)

a unit of angle, equal to an angle at the center of a circle that produces an arc length equal to the radius

random error

random errors are fluctuations (in both directions) in the measured data due to the precision limitations of the measurement device. Random errors usually result from the experimenter's inability to take the same measurement in exactly the same way to get exact the same number

range of motion

distance or angle traversed by a body part

rate of heat transfer

amount of thermal energy transferred into our, out of an object as heat, per unit time

reactive force

a type of force supplied by an object in response to application of a different force on the object. Friction is a reactive force

Relative humidity

a measure of how many water molecules are in the vapor phase relative to the maximum number that could possibly be in the vapor phase at at a given temperature. A relative humidity of 100% means that no more water molecules can be added to the vapor phase.

resistance

the force working against the rotation of a lever that would be caused by the effort

resistance arm

shortest distance from the line of action of the resistance to the fulcrum

restoring force

a force that tends to move a system back toward the equilibrium position

results

information acquired by analyzing data

rotational equilibrium

a state of having not net torque and no change in rotational motion

rupture

the sudden and complete failure of a material under stress

scientific method

a method of procedure that has characterized natural science since the 17th century, consisting in systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses

scientific notation

a way of writing very large or very small numbers. A number is written in scientific notation when a number between 1 and 10 is multiplied by a power of 10.

SCUBA

self-contained underwater breathing apparatus

Second class levers

levers with the resistance (load) in-between the effort and the fulcrum

Second Law of Thermodynamics

the total entropy of an isolated system can never decrease over time, meaning objects left to themselves will always trend toward thermal equilibrium, meaning that thermal energy will always spontaneously transfer from hot system to cold system

Sentinel Event

an unexpected occurrence involving death or serious physical or psychological injury, or the risk thereof. Serious injury specifically includes loss of limb or function.

significant figures

each of the digits of a number that are used to express it to the required degree of accuracy, starting from the first nonzero digit

skin drag

friction caused by the viscous nature of fluids

skinfold method

method for measuring body fat percentage using specially designed calipers to measure the thickness of skinfolds that are pinched from several specific locations on the body as inputs to empirical equations

slope

the steepness of a line, defined as vertical change between two points (rise), divided by the horizontal change between the same two points (run)

sonic boom

the sound associated with the shock waves created whenever an object travelling through the air travels faster than the speed of sound

sound barrier

sudden increase in aerodynamic drag and other undesirable effects experienced by an object when it approaches the speed of sound

specific gravity

the ratio of the density of a substance to the density of a standard, usually water for a liquid or solid, and air for a gas

specific heat

A material property that determines the amount of energy required to raise the temperature one mass unit of the material by one temperature unit.

speed

distance traveled per unit time

speeds
Spontaneous process

a process which occurs naturally on its own, without the need for work to be done in forcing it to happen.

spring constant

measure of the stiffness of a spring, defined as the slope of the force vs. displacement curve for a spring

stability

a measure of the displacement from equilibrium an object can experience and still move back toward equilibrium

stable equilibrium

a state in which a body tends to return to its original position after being disturbed

standard deviation

is a measure that is used to quantify the amount of variation or dispersion of a set of data values

standard scientific (SI) units

a system of physical units (SI units) based on the meter, kilogram, second, ampere, kelvin, candela, and mole

static equilibrium

the state being in equilibrium (no unbalanced forces or torques) and also having no motion

static friction

a force that resists the tenancy of surfaces to slide across one another due to a force(s) being applied to one or both of the surfaces

Stephan-Boltzmann Law

The total radiant heat energy emitted from a surface is proportional to the fourth power of its absolute temperature.

strain

the measure of the relative deformation of the material

stress

a physical quantity that expresses the internal forces that neighboring particles of material exert on each other

Study strategy

a thoughtful and specific process for self-directed learning.

support base

region defined by lines connecting points of contact with the supporting surface

Systematic errors

an error having a nonzero mean (average), so that its effect is not reduced when many observations are averaged. Usually occurring because
there is something wrong with the instrument or how it is used.

temperature

a measure of the average kinetic energy of the particles (e.g., atoms and molecules) in an object, which determines how relatively hot or cold an object feels

tension

the force that is provided by an object in response to being pulled tight by forces acting from opposite ends, typically in reference to a rope, cable or wire

terminal speed

the speed at which restive forces such as friction and drag balance driving forces and speed stops increasing, e.g. the gravitational force on a falling object is balanced by air resistance

test conditions

an item or event of a component or system that could be verified by one or more test cases, e.g., a function, transaction, feature, quality, attribute, or structural element

theory

an explanation of an aspect of the natural world that can be repeatedly tested and verified in accordance with the scientific method using accepted standard protocols

thermal conductivity

a measure of a material's ability to conduct heat

thermal energy

energy stored in the microscopic motion of atoms and molecules (microscopic kinetic energy)

thermal equilibrium

a two systems are in thermal equilibrium when they do not exchange heat, which means they must be at the same temperature

thermal expansion

The increase change in volume of an object resulting from a change in temperature.

thermal image

image created by substituting visible color variations for temperature variations determined by measuring variations in thermal radiation intensity and/or wavelengths

thermal insulation

materials designed to slow the rate of heat transfer

Thermal power

rate at which chemical potential energy is converted to thermal energy by the body, batteries, or heat engines. Also, rate at which thermal energy is converted to electrical energy by a thermal power plant.

thermal radiation

Electromagnetic radiation spontaneously emitted by all objects with temperature above absolute zero.

thermometer

a device that measures temperature

third law pair forces

a pair of equal and opposite forces applied between two different objects as described by Newton's Third Law of Motion

tipping point

the point at which an object is displaced from a region of stable equilibrium

toe region

range of values for stress and strain over which a material experiences large strain for relatively small stress due to un-crimping

torque

the result of a force applied to an object in such a way that the object would change its rotational speed, except when the torque is balanced by other torques

torques
translational equilibrium

a state of having no net force and thus no change in translational motion, though the net torque may be non-zero

translational motion

motion by which a body shifts from one point in space to another (up-down, back-forth, left-right)

transparent

allow light to pass through with minimal absorption

transverse

situated or extending across something, (crosswise)

ultimate strength

the maximum stress a material can withstand

uncertainty

Amount by which a measured, calculated, or approximated value could be different from the actual value

uncrimp

non-permanent re-alignment of substructures (fibers) in a material that results in non-linear behavior at stress values less than the yield stress.

under water weight

apparent weight when submerged in water

uniform circular motion

motion of an object traveling at a constant speed on a circular path

uniformly

in a way that is the same in all cases, across a defined set of space and times

unit analysis

act of ensuring that the units resulting from a calculation match the type of quantity calculated.

Universal Law of Gravitation

every particle attracts every other particle in the universe with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers

unstable equilibrium

a state of equilibrium such that when the body is slightly displaced it departs further from the original position

useful work

work done on the external environment, such as moving objects, as apposed to work done internally, such as pumping blood

variable

a factor, property, or condition that can change during an experiment

vectors

a quantity having direction as well as magnitude

velocity

a quantity of speed with a defined direction, the change in speed per unit time, the slope of the position vs. time graph

viscous

a fluid that exhibits a large degree of internal friction (between sections of the fluid moving with different speed or direction)

visible spectrum

the portion of the electromagnetic spectrum that is visible to the human eye

volume

a quantity of space, such as the volume within a box or the volume taken up by an object.

Watts

international standard unit of power, equal to one Joule per second

wavelength

the distance between successive crests of a wave, such as a sound wave or electromagnetic wave

weight

the force of gravity on on object, typically in reference to the force of gravity caused by Earth or another celestial body

wind chill effect

Increase in rate of heat loss from objects that are warmer than air caused by the flow of air across the object surface.

Work

A quantity representing the effect of applying a force to an object or system while it moves some distance.

work-energy principle

the change in kinetic energy of an object or system is equal to the net work done on the object or system

yield point

the value of the stress (yield stress) and strain (yield strain) beyond which a material will maintain some permanent deformation