The Fundamentals of

PHYSICS

Volume I

Force and Motion

Instructor's Guide

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To the instructor

Approach

> The fatal pedagogical error . . . to throw answers, like stones, at the heads of those who have not yet asked the questions. Paul Tillich (as quoted by Julian Weissglass on page 59 of *Exploring Elementary Mathematics*, 1979, W.H.Freeman & Co.)

Ideally, content is provided in response to questions. In this respect, all texts necessarily fail. Without one-on-one interaction, it is impossible to wait until students ask a question in order to provide the content.

This text attempts to address this deficiency by providing puzzles at the beginning of each chapter and questions (representing common student concerns) at regular intervals within the text to initiate the introduction of new content.

These puzzles not only provide the rationale for the readings but are designed to promote questioning on the part of students. The instructor is expected to support this approach by first allowing students to explore concepts, phenomena or situations much like those in the problems and investigate *what* happens before providing the explanation of *why* it is happening.

The readings are designed to support such an approach (i.e., exploration and investigation before explanation) as the selection of the content within the readings has been guided by questions I anticipate students may have.

Of course, providing answers in response to questions is not sufficient. We must also ensure that the student understands the answer. Unfortunately, even the most lucid explanations will not be fully understood or appreciated by most students. For this reason, it is the instructor's responsibility to make sure that students are given the opportunity to evaluate their own understanding.

It is recognized that the student is in the best position to evaluate whether they fully understand the material. Neither the text nor the instructor can adequately do this.

At the same time, many students are not yet able to independently evaluate their own understanding. The result is a blind acceptance of "teacher-generated answers" even in cases when the answers fail to match the student's own conceptual understanding of how the world works. Such information is simply forgotten soon after the course ends, if not before.

It is expected, therefore, that instructors will structure the course in such a way that students are encouraged to participate in continuous self-assessment. In support of this, the readings provide "example" problems within the readings as a basis for the exploration, with "checkpoints" (for student self-assessment) at the end of each section. The checkpoints are provided at the end of each section rather than at the end of the chapter so that students have an opportunity to evaluate their understanding before moving on to another concept.

Note that these problems are called "checkpoints" instead of "homework" or "practice" because it is crucial that both the text and the instructor stress the importance of active learning (sometimes called "active thinking") and self-assessment. The checkpoint questions are designed so that students can answer them quickly without going through a lot of calculations. An answer key to the checkpoints is provided, and the instructor is strongly encouraged to make it available to students.

At the end of each chapter, there are additional problems. These are the typical physics problems usually assigned for homework and practice.

✍ It is common for students to short-cut the process by reading the checkpoint or problem first and then reading "backwards" to find the answer. Emphasize to the students that they shouldn't do this. Sometimes the checkpoint or problem only addresses a small part of the readings or may merely ask the student to recall a portion of the reading, so reading "backwards" may be sufficient for answering the question but will cause the student to miss the over-arching "big idea." In other words, just because a student can answer a checkpoint or problem correctly does not necessarily mean that the student understands the readings.

Students should be encouraged to reflect on the main ideas. As such, important ideas are highlighted in the margins. At the end of each chapter, there is a summary that reflects upon these important ideas.

Ultimately, the long-term goal is for the student to evaluate his/her own understanding, continually and habitually, as the student is in the best position to do so accurately.

It is important to note that this text only *supports* what the course should be asking the student to do. It assumes the instructor has structured the course in such a way that supports the cycle of exploration and evaluation described above. The instructor is expected to avoid being the "source of all information" as such a role de-emphasizes the need for students to evaluate their own learning.

This is not easy to do for most instructors. Indeed, one shouldn't be surprised if, as the instructor, you find it difficult to "guide" your students' learning. In my experience, there are four major hurdles that must be overcome.

First, students must "buy into" the idea that the "instructor as guide" model is better than the "instructor as the source of answers" model. The instructor must actively "sell" the idea that it is best to have a classroom in which the instructor guides student self-reflection and evaluation of concepts. As part of this, you might want to provide evidence that supports this contention.

Second, the instructor must provide enough "scaffolding" so that students are prepared to evaluate their own learning. The textbook has been constructed to scaffold the necessary concepts but many students simply do not have the skills to evaluate their own learning. Even if they want to, some students cannot carry out their self-evaluation without some support. This can be very time consuming for the instructor and may be quite difficult given the background of the student and/or the number of students in the class. Still, it is imperative that the instructor recognize that many students do not automatically have the skill to evaluate their own learning and thus the instructor must be supportive and understanding of problems students will inevitably encounter.

The third problem comes from ourselves. More often than not, you may find yourself giving students "the facts," using the rationale that there is no easy (or time-efficient) way to have students explore or evaluate the concept or skills in question. In many cases, a little thought or collaboration will reveal that, on the contrary, it *is* possible. In almost all cases, a little research into what has been done by others will show that others have already found a way to address the problem in a time-efficient way. The instructor is encouraged to look into the published literature outlining the methodologies that support the learning cycle and student inquiry. It need not be an earth-shattering change in one's instructional technique but it does need to be a purposeful change.

The fourth problem is that students are not all alike. This makes life difficult for the teacher, especially in a large class. The solution is to provide enough designed-in flexibility so that different students can arrive at the goal by different paths.

Mathematics

This is a physics textbook, not a math textbook. Its purpose is to help students learn physics. While math is an important tool in physics and physics is often used to help students learn math concepts they didn't master in their math classes, a conscious decision has been made to only use an amount of math that is crucial for helping us do the physics. This philosophy leads to the following characteristics of the book.

- While it may be traditional for a physics textbook to start off with a chapter on the mathematics students will use, such an approach is not used here because (a) I don't want students to confuse the math for the physics and (b) it goes against the philosophy of introducing content as needed. As the instructor, you need to try to avoid addressing these items prior to the question arising in an attempt to be preemptive. Take the time to address it when the students see the need. The key is to provide information in response to a need, not before, and not long after. This means the instructor needs to be vigilant. We expect students to already be familiar with mathematical concepts like units, ratios and algebra, but most are not. So if you see that students are confused about a mathematical concept, you need to address it.[i]

[i] I have found that a sizable number of my students have little understanding of what a fraction like 3/5 represents. They cannot tell you whether 3/5 is smaller or larger than, say, 7/9. This is not due to lack of computational practice but rather a reliance on rote methods of solving numerical problems. In other words, they are unaware of

- Detailed information on the mathematics of things like units, scientific notation and significant figures is relegated to the supplemental readings. Any mathematical tools that are necessary for doing the physics, however minor, is introduced and acknowledged as needed. For example, explicit information is provided regarding what equations are and how quantities are represented in an equation.
- I try to emphasize the distinction between math and physics. For example, when I use trigonometry on vectors not aligned with the component directions, I offset this from the margin to emphasize which part of the problem is math, not physics.
- Mathematical terminology is avoided, especially if the mathematical term is likely to be foreign to the students. For example, while it is mentioned in the textbook that it is common to use the term "normal force" to refer to the force exerted by a surface that is directed perpendicular to that surface, the book instead uses the term "surface repulsion force".
- The book doesn't examine in detail many of the mathematical tools used by physicists, like scaling and dimensional analysis. While it has been painful to not include these things, they aren't necessary to comprehend the big picture, which has to do with the relationship between force and motion.
- Complicated algebraic manipulations are avoided. While it is neat to see how one can use complicated algebraic manipulations to solve problems, it doesn't help students to see the physics any clearer.
- While most textbooks uses 9.8 N/kg as the gravitational field strength due to Earth near Earth's surface, the book uses 10 N/kg. The error is only 2% but I've found that 9.8 makes the problems unnecessarily complicated, which can distract the student from the primary idea. The disadvantage of using 10 instead of 9.8 is that the results will many times need to be rounded to only two digits. Sometimes this is possible but other times it

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what a fraction means and, more importantly, have managed to get through many years of mathematics without developing a sense of numbers and symbols, or even recognizing that a sense of numbers and symbols is necessary. These students will have a very difficult time with this textbook because it does not provide the algorithms they rely on. Do not expect that such students will transition easily to an approach that emphasizes sense-making. While practically every one of my students has the ability to interpret and make sense of numbers (as evidenced by their ability to interpret one-half, for example), it is very difficult for students to transition from a mode that relies entirely on the application of rote algorithms to one that relies on number and symbol sense.

is clearer to provide three digits, even though I know that the result is not quite correct. I do this because I feel the purpose of the book is to practice applying the ideas, and if the numbers are a little off that is okay. In the lab, they should be learning how to test the ideas and, in those cases, they should use a more precise value for g, ideally one that is appropriate for their location. And in those cases, even 9.8 may not be good enough.

- As you can probably guess by my use of 10 N/kg for g, I don't adhere strictly to the rules of significant figures. The focus of the book is on mastering the skill of applying a small set of general principles to a large range of situations, not on getting measurable and testable results. That role is delegated to the laboratory. It is in the laboratory where students should learn about uncertainty due to resolution and precision, and where it becomes important to keep track of that uncertainty. Even there, the method of significant figures is a rather poor method (so there is no need for the textbook to reinforce the idea that it is a good method). In any event, I have found that students can easily understand why we need to be more careful about rounding in the laboratory.
- Finally, and in some ways most importantly, I purposely avoid listing a series of steps that students must follow to solve problems. Students will likely be frustrated by this at first but I find providing "steps" just feeds into their perceived need to use a technique that doesn't require any understanding of the physics. This is especially true for those students who have managed to get by in their mathematics classes by memorizing solutions used in similar-looking problems. Instructors can inadvertently reinforce this problem-solving technique by mandating that students follow a particular problem-solving approach. To counter this, I emphasize that one must first identify the physics in a *qualitative* manner before trying to solve the problem. In other words, students need to think about the physics principles that are involved prior to doing any math, and only use an equation if their analysis of the problem requires a numerical solution that can only be obtained from the equation.

Content

The textbook tries to adhere to one underlying principle: new content is introduced only in response to a perceived need, with one concept introduced at a time. This means that before studying some aspect of physics, students must not only be exposed to the rationale for studying it but it must be clear how the new content addresses a current weakness.

In keeping with this philosophy, the focus of the first chapter is not only to introduce the meaning of the word "force" (as used in physics) but also explain why we want to do that, which has to do with how the force (as we use it) allows us to predict the change in an object's motion. The first chapter also explains why there is value in relating the force and the change in motion, in that it provides an ideal context for exploring how to use a general principle to a large number of situations.

An analogy is drawn between using physics and using maps. Rather than memorize the route between every combination of two locations, we instead learn the basic principles of maps and then use that to get wherever we want to go. Many people have not mastered the ability to read a map. Consequently, they are lost without someone (or some program, like Google maps) telling them where to go.

The same is true with physics. Rather than learn the basic ideas, students try to memorize all of the different combinations. To transition students away from memorization and toward application of general concepts, the content is presented in a purposeful way, with each chapter focusing on a single idea.

Part A introduces the law of force and motion, more commonly known as Newton's second law. I don't refer to it as Newton's second law because that name doesn't tell students what the law is all about. I also want students to focus on the idea, not the name of the person typically credited with first identifying the law. So, instead of Newton's first, second and third laws, I call them the law of inertia, the law of force and motion, and the law of interactions.

When written in equation form, the law of force and motion is referred to as the force and motion *equation*. In this way, I hope to distinguish between the idea and the mathematical representation of that idea. Similar language is used for other ideas. For example, the gravity equation is the mathematical representation of the law of gravity, and the friction equation is the mathematical representation of the law of friction.

Throughout part A, acceleration is not a calculated quantity. Instead, the force and motion equation is expressed in terms of $\Delta\vec{v}$, the change in velocity. The reason for this is two-fold. First, students need to recognize that the velocity is changing *while* the object is experiencing a force imbalance.[ii] In addition, students have a difficult time with ratios, so introducing acceleration at this point only confuses the distinction between velocity and its change.

Students also have difficulty using positive and negative to keep track of directions, particularly when it comes to $\Delta\vec{v}$. While assigning a direction to $\vec{v}$, and using positive and negative for opposite directions, is straightforward for students, assigning a direction to the *change* is not so straightforward. For this reason, the focus is more on using the law of force and motion to determine if the object is slowing or speeding up, and *then* using the force and motion to determine *by how much* the object has slowed or sped up.

The force and motion equation also provides the context for reviewing mathematical notation, and distinguishing between simultaneity, constant values and instantaneous values. The difference between vectors and scalars is also discussed, but mostly relegated to the supplemental readings. All motion in parts A through C is restricted to one dimension.

Throughout part A, the magnitude of forces are provided. In other words, gravity is not introduced, nor is the relationship between the normal force and friction. Gravity is introduced in part C, and the relationship between the normal force and friction is not introduced until part D, which examines situations in two dimensions.

To convey an idea of what a force is, without introducing specific types of forces, students are provided with a conceptual analogy of tiny invisible springs that exist between objects that either pull them together (for attractive forces like strings) or push them apart (as when two objects collide). In doing so, it is emphasized that forces are associated with interactions (i.e., the tiny invisible springs) rather than one object or the other. Forces on an object are “due to a second object”, which acts as short-hand for “due to its interaction with the second object”. For the same reason, forces can be “exerted *on* an object” but are not “exerted *by* an object”.

Chapter 5 introduces Newton’s third law, referred to as the law of interactions, which allows us to relate the forces acting on each object of an interacting pair. Chapter 6 then applies the law of interactions to collisions. The

[ii] The idea of net force is first discussed as the “force imbalance” and I return to this idea often throughout the book.

concepts of impulse and momentum, along with conservation of momentum is delayed until chapter 27.

Part B focuses on the definitions of acceleration and velocity. Chapter 7 introduces the definitions of acceleration and velocity, and examines their similarities and differences. Time-lapse pictures are introduced as a tool for visualizing the differences. Chapter 8 examines how an object's displacement is related to the object's average velocity, rather than initial, final or change in velocity. The idea of an average is discussed in this section. Don't assume that students already know what an average is. They don't. In addition, students will be confused on when they need to use the definition of average velocity to get the average velocity (from the displacement and time) and when they can just use the midrange between the initial and final velocities.

Throughout this discussion, only the definitions of acceleration and velocity are used to predict the displacement. At no point is a standard kinematic equation like $\Delta x = v_0 t + {}^1/_2 a t^2$ introduced. For one, it isn't necessary. Students can solve the same problems by first figuring out the change in velocity then, from that, determining the average velocity then, from that, determining the displacement. In addition, using the two definitions (rather than one combined equation) provides the context for exploring how to use multiple ideas sequentially within the same problem.

Yes, it is easier for students to use a single kinematic equation. However, I've found that only allows students to solve the problem without thinking about the physics. Besides, using a "replacement" equation in place of the basic laws and definitions just reinforces the rote algorithm mentality we are trying to move away from.

At this point, the four main ideas of the book have been introduced (law of force and motion, law of interactions, and definitions of acceleration and velocity). One must emphasize to students that the same four ideas will be used over and over again throughout the book. Sometimes only one will be needed for a particular case and sometimes more than one will be needed, and the order we use them is not necessarily the same in all situations.

Graphs are introduced in chapter 10. Notice that this is *after* the definitions of acceleration and velocity rather than as a tool for understanding the definitions. This is because I've found that graphs confuse students more than help students because many never really learned graphs. Indeed, many students think of a positive sloped line as representing an object that is moving up and to the right, regardless of whether the axes indicate position, velocity or time. Consequently, a separate chapter on graphs is provided that explains how to use graphs, while providing some insight into the definitions of acceleration and velocity.

The last chapter of part B looks at oscillations. This provides a context for applying the ideas of the previous three chapters and relating it to the law of force and motion. This also provides the context for introducing terminology like cycle and period, which are used in part E.

As the instructor, you may tempted to postpone the oscillations chapter until later. You can probably do so without too much disruption. It is placed at this point because oscillations provide a great way to illustrate the difference between velocity and acceleration. However, it considers a situation where the force is not constant, and the rest of the book focuses on constant forces for the most part.

As mentioned before, one unique aspect of the book is that gravity is not introduced near the beginning. This is done because the concept of gravity is a difficult one for students. By part C, however, it is hoped that students can recognize two crucial things that allows for the study of falling objects: that gravity is associated with an interaction, rather than being an intrinsic property of an object or a consequence of other forces, and that an object accelerates while a force imbalance is acting on it.

In part C, then, we look at the motion of objects when the gravitational force is acting. The first chapter of this part introduces the universal law of gravitation, with an emphasis on what it means for the force to be associated with both of the objects that are interacting. In chapter 13, the mg expression is introduced and explained, with g representing the gravitational field strength. Common areas of confusion are also discussed, including the difference between the gravitational force, the gravitational field, air pressure and mass. I also discuss why I avoid the use of weight and pounds.

Free fall is examined in chapter 14, with free fall defined as any situation where the gravitational force is the only force acting. That means that both rising and falling motions can be considered free fall, if no other forces are acting.

Chapter 15 introduces additional forces, including drag, the force due to strings, ropes and cables, and the surface force. These are applied to typical vertical problems like elevators and terminal velocity, keeping to the one-dimensional nature of all the problems examined up to this point in the book.

In this chapter, a distinction is made between the tension in a string, rope or cable, and the force due to the string, rope or cable. The former is a scalar and the latter is a vector. For ease of reference, many people call the latter the tension force but for consistency I call it the force due to the string, rope or cable.

Since friction isn't being considered, the force due to the surface is simply called the surface force. While it is noted that the force is in the normal direction, there is no need to call it the normal force, since a frictionless surface only exerts a force in the normal direction. Separating the surface into two components, normal and friction, isn't necessary until part D.

Two-dimensional motion and forces are examined in part D.

Projectile motion is examined in chapter 16. This is introduced first because it involves the same vertical forces introduced in part C, with the only added complication being the introduction of horizontal motion, allowing us to treat each component separately. Velocities are treated as the sum of two perpendicular components, rather than a single magnitude and direction so that students do not yet need to use any trigonometry.

Chapter 17 examines horizontal surfaces with friction. Friction is also introduced, but no distinction is made between static and kinetic friction (in other words, the kinetic friction is equal to the maximum static friction). It is at this point that the surface force is separated into two components: the surface repulsion force and the friction force. Since the horizontally-directed friction depends on the vertically-oriented normal force, the two perpendicular components of the net force are not independent, which adds a complication to the process of solving problems in two dimensions.

Trigonometry is introduced chapter 18 as a way to break up a vector into components. By delaying trigonometry until this point, I hope to make clear that the math only helps us do the physics, it doesn't replace the physics. To reinforce this, the analysis of each example problem starts and ends with physics, with the trigonometry part offset from the margin slightly.

To help students who are weak at trigonometry and to move away from mindless rote application of trigonometry functions, students are guided to first determine which component should be bigger based upon which axis the vector is more closely aligned. Rather than memorizing which component corresponds to the cosine and which the sine, they can calculate both and then use the one that is bigger or smaller, consistent with what they expect.

One notable deletion is a discussion on how to obtain the direction of a vector from components (i.e., inverse trigonometric functions). This has been relegated to the supplemental readings, as it is not crucial for the physics.

Applications of trigonometry are examined in chapter 19. Objects on inclines are examined in the supplemental readings. While they provide a context for exploring our choice of coordinate orientation, this is not considered important for this audience and does not affect future chapters.

The first chapter of part E looks at circular motion. This provides the context for discussing the idea of reference frames. Since gravity has not yet been introduced, all instances of centripetal forces use force magnitudes that are provided (rather than the students having to figure them out). This chapter also examines orbits and the difference between global vs. local gravity.

The second chapter of this part looks at rotation. This provides the context for discussing angular quantities and units.

The third chapter of this part looks at how the circular descriptors are related to the rotational descriptors. This is necessary for the fourth chapter, which looks at torque and its impact on rotation. The idea of rotational inertia (moment of inertia) is also discussed, but equations for each object shape is not provided. Instead, students should be able to determine relative values of rotational inertia based upon the shape.

The last chapter of this part, chapter 24, applies the ideas of torque and rotation to the idea of balance.

Part F looks at energy. While frequently introduced along with momentum, we have purposely separated it so that students are less likely to confuse the two. While they both can be used within the context of conversation, that is not the main purpose of introducing it at this stage within the textbook. Instead, energy allows us to make predictions that don't involve time.

Chapter 25 does this via the concept of work and kinetic energy. Students are told that forces act as mechanisms to transfer energy to and from kinetic energy, and the amount of energy transferred is equal to the work done by that force (product of the force and the distance the object travels parallel to the force). As with $\Delta\vec{v}$, students are instructed to pay more attention to whether the object should speed up or slow down (based on the force direction relative to the motion) than the actual sign of the work. The main point is that we can these ideas are perfectly suited to situations where the time is not given. Not only are situations explored where time is not given, but also situations where mass is not given (but acceleration is).

Conservation of energy is introduced in chapter 26, along with what it means for energy to be conserved and what are some different forms of energy. A distinction is made between constancy and conservation. Energy is always conserved, but it isn't always constant for a particular system. A conserved quantity cannot be created or destroyed, and the only way a conserved quantity can change in one region or object is if some of it is transferred to or from an adjacent region or object. This means that the quantity may not be constant within a particular region but it is always conserved.

Conservation of momentum is introduced in chapter 27. The point here is that using momentum conservation allows us to solve the same problems as before but more simply, plus it gives us the tools to do additional stuff, like problems involving rotation (conservation of angular momentum).

Relative motion and thermodynamics are not included in the textbook. Fluids are discussed in volume II.

Suggested timeline

The book is designed to be used at a pace of one chapter per class meeting.

With a day devoted to assessment after each part of the text, along with an extra day for review, this corresponds to 40 class meetings. For a class that meets three times a week, this corresponds to 14 weeks minus two class meetings. This allows for two extra days for an introduction to the course, a review for a final, or extra time on those chapters that are particularly long, like chapters 23 (Predicting Rotational Motion), 10 (Graphs) and 25 (Work and Kinetic energy).

If you need to skip a chapter, you can skip chapter 11, chapter 24 (Balance) and/or the two-dimensional chapters 18 (Obtaining Component Values) and 19 (Applications in Two Dimensions) without impacting future chapters.

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