The Tiger
and
the Physicist

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Insights into the Physics We Teach

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Preface

> Tigers ... never waste energy. A tiger never runs harder than necessary to catch another animal, never jumps higher than needed to clear an obstacle, never moves around without a reason.
>
> Tom Brakefield, *The Lamp*, Spring, 1996

For tigers, conserving energy is a matter of survival. A tiger will choose the easiest path to reach a goal. But even tigers fall into traps.

Herbert Linn, in his doctoral thesis at MIT on problem solving (1979), pointed out that problem solvers, also, tend to choose the easiest path. If the easiest method does not work, then a more difficult approach may be attempted. And problem solvers sometimes fall into traps.

It appears, when it comes to teaching physics, we are tigers. As a matter of survival, we accept the easiest path, until we find that path inadequate. We have seen great efforts in recent years on how to improve teaching, with new styles of presentation, more student involvement, and new sequential orders of presentation. It is time to look, also, at what we teach. (This could be described as content *vs.* methodology, but "content" is usually interpreted as the syllabus. We are more concerned here with the details, within the standard syllabus.)

Some parts of basic physics have been simplified to the point they have become illogical and thus no longer understandable. Other parts have come as a gift-wrapped package with a label — "swallow this whole and you will be smarter than other people". We all have a strong bias toward accepting the information we acquire first, whether it is from an instructor or a textbook or another source. When this information is wrong, students learn incorrect physics, which is therefore incompatible with other parts of physics.

It seems a safe generalization that no one understands all of physics. We all make mistakes, and we all have gaps, or blind spots, in our understandings. One often suspects that every physicist goes through his or her career hoping no one will find out how much he or she does *not* understand. For a variety of reasons, available textbooks have errors and omissions that impede understanding.

Many errors arise from partial truths. We tell students that force times distance is called work: $W = \int \boldsymbol{f} \cdot d\boldsymbol{s}$. Is it wrong? Only sometimes. A student learns that the speed of light is $v = c/n$ and $n \geq 1$. Is it wrong? Only sometimes. A student learns that a projectile near the Earth follows a parabolic trajectory. Is it wrong? Only negligibly so, usually.

Many errors arise from extrapolations of valid equations into regions of invalidity. A thermodynamicist envisions a closed system sitting on a laboratory bench and writes $\Delta E = Q + W$, specifying that ΔE is the change in internal energy. Another physicist envisions a "physical particle" (which can change *only* kinetic energy) acted on by a force and writes $W = \Delta(K.E.)$. Each is copied into textbooks, without adequate warnings that they are mutually incompatible,. Each is memorized and repeated by generations of students (and therefore teachers) as if they were general equations.

Good teachers may say, "Surely we understand what we mean when we say ...", but this understanding may or may not extend to the intended audience of students. They may believe what we say!

With the enormous time pressures felt by most physics teachers today, both to cover more material and to meet responsibilities outside the classroom, it is not surprising that we feel satisfied if we can simply teach a substantial fraction of what is in the texts, without attempting to revise the material. But repeating to students what is in the textbook should no longer be considered acceptable. We really can do better. *Correct physics is easier than memorized "simplified" physics because it is self-consistent.*

The questions raised in this presentation come from a variety of sources. Some express difficulties students experience when they study from contemporary textbooks, or difficulties the author recalls facing in learning and teaching physics.. Most are based on errors or omissions from published textbooks, articles, or notes, or from manuscripts submitted for publication. Many points raised are “well known” sources of frequent difficulties. Some topics were included at the request or suggestion of reviewers. Some are insights acquired during a career of teaching. What almost all have in common is that they are questions that have caused difficulties for good students and for good physicists. But a few are just for fun.

Although there is no intent to keep this presentation out of the hands of students, it is written for physics teachers, rather than beginning students. Therefore a general background in physics is assumed on the part of the reader, which permits topics to be grouped more logically than if it were necessary to build the presentation in a semblance of linear structure. Most of the topics are directly from first-year physics courses, and will therefore not be unfamiliar to readers, but some provide background that should aid in understanding the introductory material. It is not suggested that the full explanations provided here are appropriate for students in an introductory course, but understanding the background may help prevent propagation of misleading or erroneous explanations to the students. A few of the more advanced topics may be considered more a warning against common over-simplifications than an explanation of the topic itself.

The format is designed for quick reference. It was a severe temptation to fill in between the selected bits and pieces to provide better continuity. However, because most teachers are already well aware of this background, its inclusion would dilute, and therefore hide, the points that need emphasis. Some important topics will appear to be slighted, because they are usually adequately discussed in current textbooks.

Although references are provided to some sources, there is no claim that all relevant contributions have been acknowledged. A series of publications appeared over many years in *The Physics Teacher*, by Mario Iona, under the title “Would You Believe ...” These dealt with errors and misleading statements appearing in science textbooks for elementary students. As implied by the title, few physicists would fail to recognize the errors to which attention was called. By contrast, attention is directed in the present work to topics that are usually presented in a manner so consistent with the physics we learned, or with difficulties so subtle in character, that the common errors may not appear obvious.

The publication by J.W. Warren, “The Teaching of Physics” (Butterworths, London, 1965) concentrates on problems observed in sixth-form level physics and the attendant examinations. Every physics teacher should be aware of these common misstatements and misinterpretations, dealing largely with problems that arise from teaching the phenomenology of physics beyond the range of understanding of the theory, and/or the extension of the equations of physics beyond the conditions for which they are valid. There is surprisingly little overlap of content between that work and this.

Discussions emphasizing how material should be presented have been given by Arnold B. Arons, "A Guide to Introductory Physics Teaching" (Wiley, New York, 1990) and "Teaching Introductory Physics" (Wiley, New York, 1997) and by Randall D. Knight, "Five Easy Lessons" (Addison Wesley, 2004).

If you find something with which you disagree, please do not ignore it. It is almost certainly a point on which there is misunderstanding. Let's find the misunderstanding and clarify the point.

It is the author's hope that this selection of insights will increase the sensitivity of teachers and students for some of the basic physics with which we are all familiar, and encourage a more critical look at introductory physics. We would all be well advised to heed the words from the *Principia:*

> *I heartily beg that what I have here done may be read with forbearance; and that my labors in a subject so difficult may be examined [as I have examined the labors of others], not so much with a view to censure, as to remedy their defects.*
>
> Sir Isaac Newton

Birmingham, Alabama 2008 *Robert P. Bauman*

Acknowledgments

Physics is a community effort. Many individuals have contributed to the development of the theory and practice of physics, including, but not limited to, contributions of published notes, papers, and textbooks. Any commentary on physics necessarily relies on this accumulation of material, including explicit observations and proofs and interpretations that are implicit in the theory as developed. The author is indebted to all of these contributors, but special acknowledgment is due to those who have read and commented on earlier drafts of this material, in various forms, or commented on specific questions. Their counsel is greatly appreciated.

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Introduction

Sample Topics

Which of the following dozen topics are adequately treated by the textbooks you currently teach from? (Question numbers where each is discussed are appended.)

1. Physics tells us the cause of motion. I.3.2; II.1.2.
2. If a fluid moves faster it will exert a lower pressure. IV.2.1.
3. A round object rolling on a plane surface should exhibit no friction III.3.1.
4. "Centrifugal force" is out of date and should be replaced by centripetal force. IV.2.4.; V.2.1.; V.4.2.
5. The theory of relativity tells us mass and energy can be interconverted, but the proof requires advanced mathematics. X.1.3.
6. Gyroscopes follow rules of angular momentum vectors, rather than Newton's first and second laws. V.3.1.
7. A sudden pull on a cord can break the cord below a large mass before the mass is set in motion. II.5.8.
8. Conservation laws apply to isolated systems. 1.3.7.
9. Left to itself a system generally goes to a lower-energy state. VII.1.3.
10. The "North Magnetic Pole" is actually a "South Pole" located below the surface of the Earth near the geographic North Pole. VIII.4.1.
11. A good telescope should give a large magnification. IX.4.3.
12. Sound is a longitudinal vibration in air, transmitted by molecular collisions, so the speed of sound must be approximately equal to the speed of air molecules. V.6.1.; V.6.4.

Definitions

Certain concepts appear frequently in physics literature and in the discussions. For clarity, the terms are defined, as they appear here, and a reference given to where they appear.

1. A *physical particle* is an object, of any size or shape, that can change its kinetic energy, *only*. (V.36)
2. A quantity is *conserved* if it remains constant for *all* processes, and all conditions, for the system and the surroundings (or for the universe, defined locally). (1.3.7; V.78)
3. A quantity is *preserved* if it remains constant for the system under the conditions specified. (1.3.7)
4. *Work* is a transfer of energy (from surroundings to the system) under (approximate) equilibrium conditions by a force acting over a distance over which the force is applied. (V.5)
5. *Heat* may mean *warming* of a system, or *thermal energy* (random) within a system, or *transfer of thermal energy* from the surroundings to a system. Because it has no single, accepted definition it is not a satisfactory technical term (although it is frequently substituted for a technical term, typically to keep the meaning imprecise, intentionally or otherwise). (V.6.)
6. A *system* is any part of the universe selected for special attention and carefully defined. (V.4)
7. The *surroundings* are all of the universe *except* the system (that might be affected by the process under consideration, to avoid irrelevant cosmological uncertainties). (V.4)

Table of Contents