Preface

This is a textbook of physics outside of the standard mold. It introduces the ideas of modern physics – relativity theory, quantum mechanics, particles and forces, and cosmology – at a level appropriate for introductory college or advanced high school students.

Why teach modern physics to students who may not have a strong background in classical physics? There are a number of reasons:

- The topics are interesting in themselves.
- Most physicists have lived and most physics has been done since 1900.
- Students read accounts of advances in physics in daily Tweets and blogs and news snips.
- Citizens are required to make decisions based on some minimal understanding of the concepts of modern physics (e.g. should Congress fund particle accelerator laboratories?)
- We live in a technological society based on the discoveries of modern physics.

While an introduction such as this one lacks the rigor of formal mathematical presentation of the material, the concepts of modern physics can be understood readily by students at this level. This textbook aims to make the concepts of modern physics accessible to any interested reader. The text itself, hopefully, explains concepts clearly, and "kitchen experiments," most of which can be performed with simple home apparatus, illustrate the ideas. The author encourages the student to perform the demonstrations, to get a hands-on feel for what otherwise may be abstract notions.

My colleague, Robert LaMontagne, in the Physics Department at Providence College contributed to the chapters on Newtonian physics and special relativity. I thank him for his clear presentation of the ideas and for his suggestions to improve the text. Any errors in concept or editing are mine alone.

The text cites material from a number of other sources, and it is hoped this introduction will stimulate further study of this, one of the greatest endeavors of the human mind.

Introduction

Physics is the study of Nature, and physicists attempt to understand the structure of the Universe, what it is made of and how it works. Physics attempts to answer such questions, among many others, as “Why is the sky blue?;" “Why does the sun shine?;" “Why does ice float to the surface of liquid water?"

We tend to think of physics as a body of knowledge, and in the classroom it is often presented as a collection of facts. But physics is much more. It is a process, a method of learning about Nature. Working physicists, like all scientists, ask questions (e.g. "why does ice float on water?"), propose hypotheses, tentative answers, to those questions, and perform experiments to test those hypotheses. (For example, to explain why ice floats we might hypothesize that when water freezes it incorporates atmospheric oxygen into its crystal structure, which makes it less dense than water. We might test such a hypothesis by melting ice and measuring the amount of evolved oxygen.)

In order to understand how Nature works, physicists, like other scientists, build models – not wire and glue and cardboard models, but mathematical models. It is compelling that mathematics, the logical constructs of the human mind, can so accurately describe how Nature behaves and even predict natural phenomena before they have been observed in the laboratory. Typically the process proceeds as follows (Moore, 2001):

1. A scientist observes a natural event, perhaps one hockey puck colliding head-on with another puck initially at rest. In the collision, the first puck stops and the second takes off at the same speed as the first.
2. The scientist proposes a mathematical description – a model – of the event, perhaps

   $$(s_1 + s_2)_{after} = (s_1 + s_2)_{before}$$

   That is, the net speed of the two pucks is the same after the collision as it was before.
3. She then tests the mathematical model with other experiments. Perhaps she stacks two other hockey pucks on top of puck number two and finds that puck 1 bounces backward in the collision while the stack of three moves ahead but at a slower speed than before.
4. Based on the results of experimentation, the scientist revises her mathematical model to provide a better description of hockey puck collisions; apparently speed <u>changed</u> under the new circumstances. (Eventually, we anticipate, she’ll arrive at a mathematical expression that <u>momentum</u> is conserved in the collision. We’ll study this in Ch.1.)
5. Other scientists test the model under various circumstances, in different colliding systems, seeking the simplest model that successfully explains the widest range of natural phenomena – billiard balls and asteroids and car wrecks and entire galaxies in collision.

The scientific method is a way of knowing. Scientific knowledge is compelling because it is testable: if a model withstands many experimental tests, we can say with some confidence that Nature really does behave as described by the model. On the other hand, scientific knowledge is tentative and incomplete: a model may be proved wrong (as would our hypothesis concerning water ice), but it can never be proved incontrovertibly correct: new experiments, perhaps, with more sensitive equipment may find subtle discrepancies that demand a new model.

This text describes what physicists have learned about Nature, but it is not really physics, the active process of learning. Hopefully, it will provide a background of information and enough insight into the process that the interested reader might actually do physics or at least have enough background in the scientific method to distinguish substantiated scientific knowledge from speculation.

Scale

Physics spans a tremendous range of scale. Our everyday world is measured in centimeters and meters and kilometers. We drive our car (which is a few meters in length) to the store (a distance of kilometers) to buy a loaf of bread (several centimeters in length). What we experience directly, through our senses, however, is but a tiny fraction of the realm of the Universe. The diameter of an individual atom is of the order 10^{-8} cm, one-hundred-millionth of a centimeter. Smaller still, physicists describe events of a range of 10^{-16} cm (the range of the weak nuclear force), and even of 10^{-33} cm, the hypothetical size of the smallest discrete bits of matter. For rough comparison, an atom is as much smaller than a typical marble as a marble is smaller than Earth. The range of the weak force is as much smaller than the diameter of an atom as the atom is smaller than the marble.

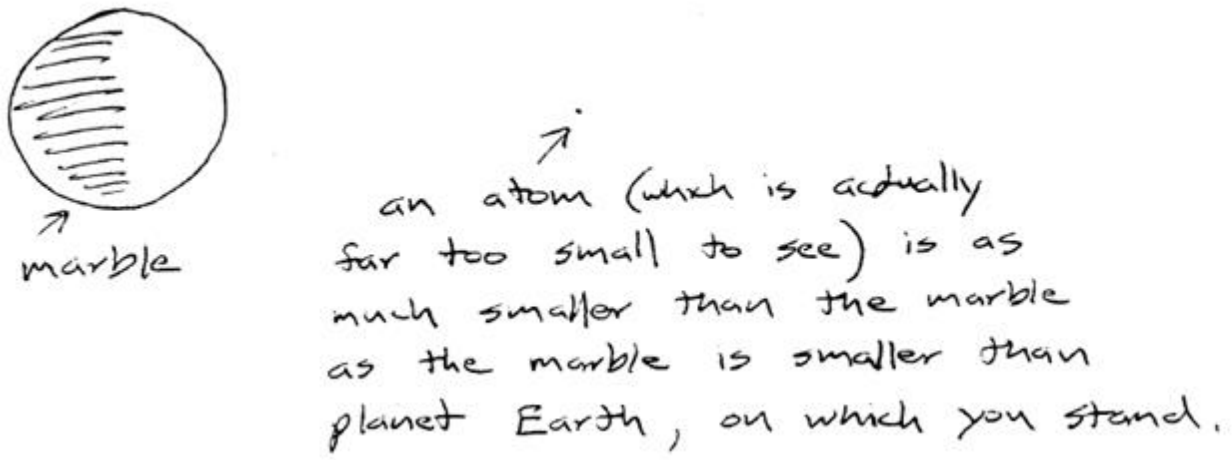


Figure I.1. Relative scales of the macro- and micro-worlds.

At the other extreme, physicists discuss stars (typically with diameters thousands of times the diameter of Earth), galaxies (typically with diameters tens of thousands of light years in diameter and including hundreds of billions of stars), and the large scale structure of the Universe (on the order thirteen billion light years in diameter and comprising hundreds of billions of galaxies.) A light year is the distance light traverses in one year, traveling at the speed of light, about 300,000 km/sec.

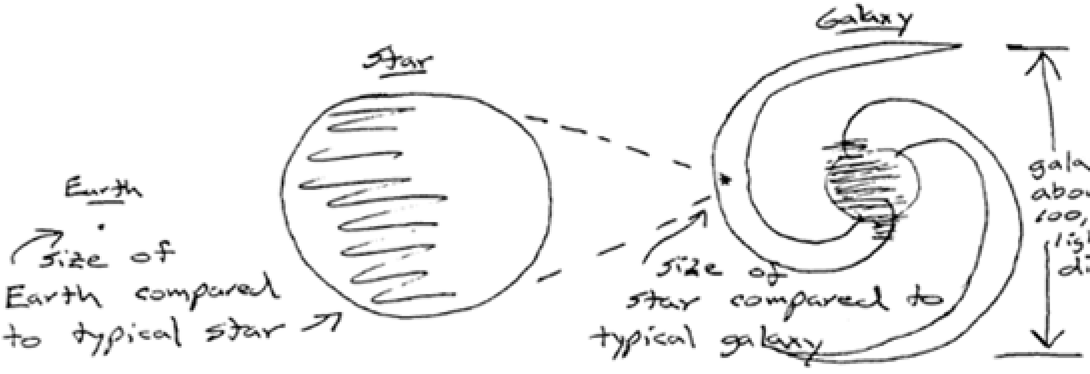


Figure I.2. Impression of the relative sizes of astronomical objects. Note that the size of a star compared to the size of a galaxy would be a much tinier dot, far smaller than illustrated here.

It is remarkable that the known laws of physics apply over such a vast range of scales, from the very smallest to the very largest structures in the Universe. In fact, as we shall see, the origin of the Universe, the largest structure, must be understood in terms of the very smallest structures, the subatomic particles and the forces through which they interact.

How physics works

There are many facets to physics. One aspect of physics is observational: in order to understand how the Universe operates, we must observe and measure it. For example, in order to understand planetary orbits, we first must track the planets' paths across the sky.

A second facet of physics might be called theoretical. Having measured a physical phenomenon, physicists seek to explain the phenomenon in terms of mathematical equations, the models. An example is Newton's law of gravitation, which elegantly "explains" why the planets move as they do.

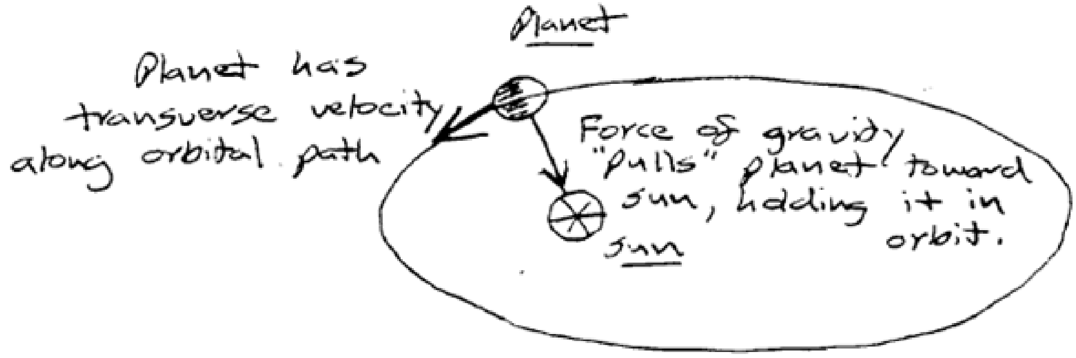


Figure I.3. Newton's model of gravity.

A third facet of physics is experimental. Physicists make predictions based on their models then test those predictions with new experiments. The law of gravitation, for instance, can be tested in the laboratory with the Cavendish apparatus.

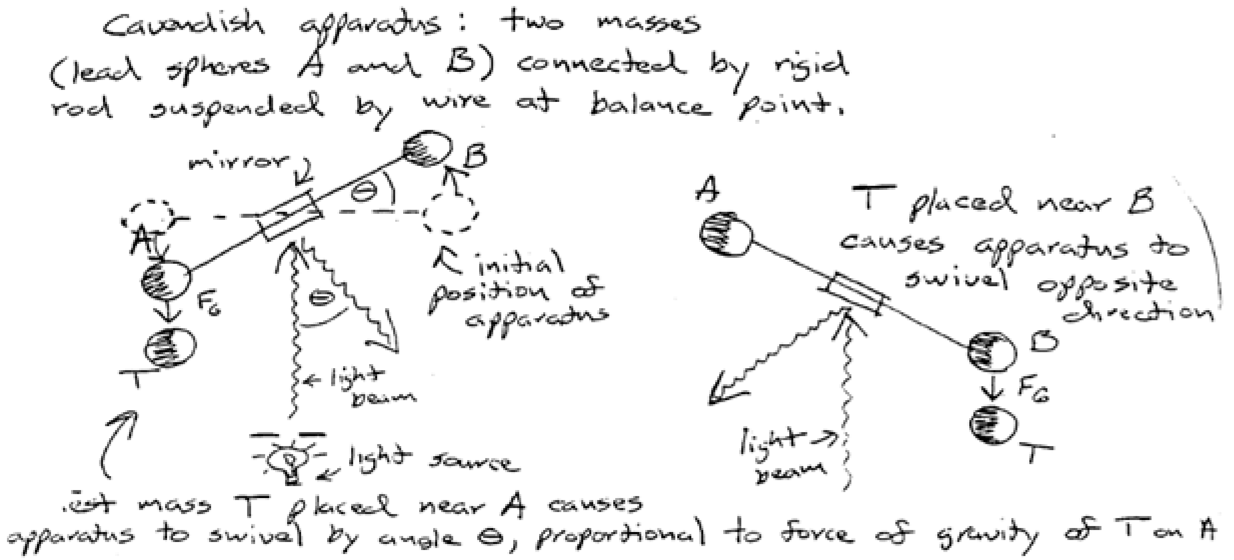


Figure I.4. Diagram of the Cavendish apparatus to measure the force of gravity between masses.

Physics advances when experimental observations contradict the theoretical predictions, requiring a refinement of theory, or when a new theory conjures new experiments.

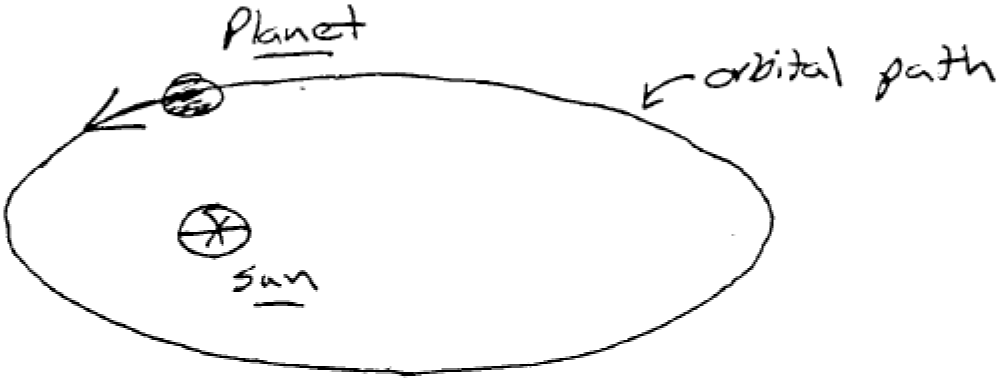
Some historical developments

There are no step-by-step instructions telling physicists how to learn about Nature. Observation sometimes leads theory, theory sometimes leads experiment, and experiment sometimes leads theory. As in all creative human endeavor, however, there is an undefinable spark – a flash of inspiration, a creative "hunch," a sudden insight – that kindles understanding.

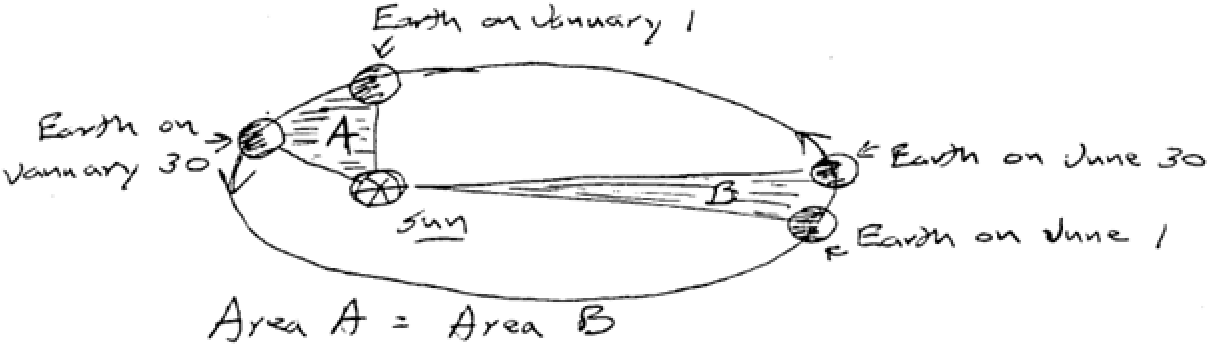
Classical mechanics (the study of matter in motion) developed roughly from measurement to theory to experiment. Tycho Brahe (Danish astronomer, 1546-1601) spent a lifetime recording the positions of the planets. Johannes Kepler (German astronomer, 1571-1630) transformed these detailed observations into a useful description of planetary motion. He determined that planetary orbits traced out ellipses and found a mathematical relation between the speed of a planet and its distance from the sun. Later, Isaac Newton (English physicist, 1642-1727) developed "laws" of motion which not only explained Kepler's discoveries but also successfully described the motion of all objects in nature. (As we shall discuss in Ch. 1, Newton's model is incomplete.)

Kepler's laws of planetary motion

1. The planets, in their orbits, trace ellipses around the sun, with the sun at one focus of the ellipse.

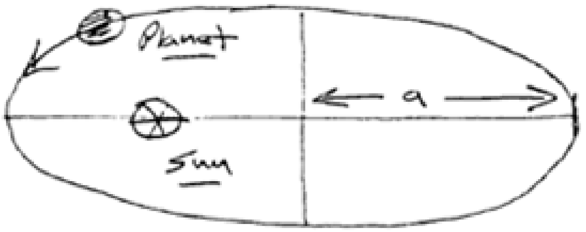


2. A planet sweeps out equal areas in the plane of its orbit in equal periods of time.



3. The square of the period (P) of revolution (the amount of time it takes a planet to orbit the sun) is proportional to the cube of the average distance from the planet to the sun.

$$P^2 = ka^3$$



where P = period of orbit = time it takes planet to go once around sun

a = average distance of planet from sun

k = a constant of proportionality (depends on force of gravity)

In contrast to the evolution of Newtonian physics, relativity theory started as theory, and the theory was later confirmed by experiment. Albert Einstein developed the special and general theories of relativity by logic alone, essentially unguided by experimental data (little appropriate experimental data was available at the time). Only after the theories had been completed on paper were they confirmed by observational test.

Quantum mechanics, on the other hand, developed from experiment to theory. Certain experimental observations early in the twentieth century, among them the observations of blackbody radiation and the photoelectric effect, could not be explained by the (then) known laws of physics. Those observations demanded a completely new theoretical basis. Physicists developed quantum theory to explain the experimental data.

The nature of physical law

In our society, truth is often obscured. Slick advertisements, often with no basis in fact, glow with claims such as "Crispy Smirdles cereal is healthier, sweeter, and crisper than any other brand." Politicians promise a balanced budget, stronger defense, and guaranteed health care for the elderly, all provided, of course, without a tax increase.

When physicists claim to have discovered a law of nature, however, they base that claim on a rigorous process of experimental test, and the claims are as accurate as the supporting experiments. To earn the title, "law of nature," that description of how Nature behaves (the model) has been tested many times, with different experiments, and each experimental test has confirmed the predictions of the law: there is no contradictory experimental evidence.

For example, the inverse square law of gravitation (that the force of gravity decreases as the inverse square of the distance between two masses) has been tested with Cavendish devices in earth-bound laboratories with kilogram weights, in particle accelerators with neutrons (about

$6 \times 10^{-27} kg$), and in space near planet- and star-size masses (about 10^{30} kg). It has always proved true, to within experimental uncertainties.

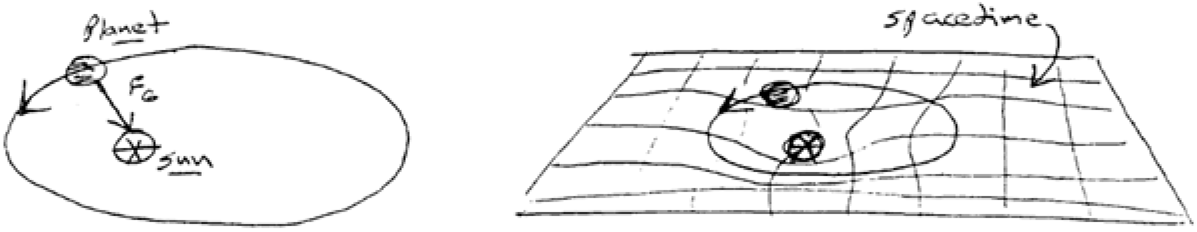
Still, despite rigorous testing, physics remains tentative and incomplete. We don't (yet) know everything about the Universe and how it operates. Theorists sometimes make mistakes, experiments are sometimes flawed, and measuring devices have limited accuracy.

We are still learning. As physicists perform more accurate experiments (as more accurate measuring devices become available) they must revise their laws to accommodate the refined data. As they probe smaller and smaller spaces within the atom, for instance, using more powerful particle accelerators, new discoveries force physicists to revise their description of the atom and how subatomic particles interact.

Models and paradigms

Physical laws are descriptive: they describe how Nature behaves, but they do not necessarily tell us what Nature is. For instance, Newton's law of gravitation allows us to predict the motion of a planet, depending on the effects of other masses pulling on it. Einstein's General Theory of Relativity provides deeper understanding of gravity in terms of masses interacting with the geometry of spacetime. But Newton’s and Einstein’s theories of gravity only tell us what gravity does, not what it is. We cannot pick up a lump of “gravity” and squeeze it and measure it. We can only describe how gravity affects the trajectories of masses.

Different mathematical models provide different perspectives on the physics. , the physical laws that provide our best current descriptions of Nature at all scales – how gravity, for example, affects the paths of planets around suns, galaxies in galaxy clusters, and quarks in a proton.



Newton's model of gravity: sun holds planet in orbit by a "cable-like" force.

Einstein's model of gravity: planet orbits sun because spacetime is curved in the vicinity of the sun (like the surface of a trampoline is curved by someone standing on it.)

Figure I.5. Two different models, Newton’s and Einstein’s, describing the force gravity.

After years of experimental test, if the model passes all tests and physicists generally accept the model in their own thinking and their own work, the model becomes the established paradigm.

Often the physicists' paradigm becomes a paradigm for the general public as well, and there is a tendency to regard the paradigm as Nature herself.

But with new experimental data, or new theoretical analysis confirmed by experiment, the paradigm may shift. At the beginning of the twentieth century, for instance, Newton's classical paradigm crumbled under the onslaught of contradictory experimental evidence and was replaced by Einstein's relativity, and probabilistic quantum mechanics has replaced Newton's paradigm of a causal and objective universe.

No-fault physics

When a paradigm shifts, that is not to say the old paradigm was "wrong." That Einstein has provided a more accurate description of gravity than Newton, for example, is not to denigrate Newton.

Newton's laws were perfectly adequate for the scales familiar to him -- the scales of falling apples and planetary orbits. Two hundred years after Newton, however, physicists had developed more accurate measuring devices that opened new scales of mass, length, and time to observation, and they had accumulated a much broader range of observations in the intervening years. Einstein could incorporate the amassed wisdom of those years into his general theory of relativity.

Newton's laws are, in fact, low-velocity, low-mass approximations to Einstein's theory. It is generally true that when a new law replaces an old, the old law is recognized as a valid approximation, at more familiar scales of measurement, to the new. The old law is still usable, if we don't quibble about the accuracy of our measurements.

Themes

In this book, we shall trace the shift in paradigm from classical physics to the present. The book is not intended as an historical treatment. However, the understanding of modern physics requires familiarity with Newtonian physics and the concept of fields. The table of contents outlines the development of ideas in the text.

An underlying theme in this book, and to the development of physics, it is the "unification" of our understanding of natural phenomena. One aspect of this unification is that the same laws of physics apply throughout the Universe. For example, light from distant stars is produced by the same processes as in our own sun, and the force of gravity behaves the same in the Andromeda Galaxy, 2.5 million light years away, as it does in our own.

Moreover, modern physicists have learned that objects and events once thought to be distinct are in fact related: electricity and magnetism, originally thought to be separate phenomena, are related. Mass and energy, originally thought to be distinct, are in fact interchangeable. There is accumulating evidence that all the various physical forces in nature are simply different aspects of a single underlying Force.

We live in a tremendously exciting age in physics. In the last century, physicists have built robust models describing the behavior of the very smallest and the very largest structures in Nature. As of this writing, the great challenge to physics is the unification of quantum mechanics, describing interactions at the smallest scales, with general relativity, the model describing Nature at the largest scales.

A word on why

The question arises in the classroom, "So what?" So electrons can be described as waves. So what? So gravity can be described in terms of geometry. So what?"

One can defend the study of physics from a number of perspectives (besides having to do well on physics tests in school!):

- We live in a technological society. Our TV's, wristwatches, automobiles, and computers use technologies discovered from principles of quantum mechanics. In medical care, machines such as linear accelerators, CAT scans, and PET scans save lives. Those machines were developed using principles discovered in the study of particles and forces.

- As citizens participating in our government, we face decisions that require an understanding of physical principles. Is nuclear energy a viable, safe energy source? What is the physical basis of the greenhouse effect, and what, if anything, should be done to avert possible ecological changes associated with greenhouse warming? Should we spend taxpayer money to build particle accelerators?

- An awareness of physical principles enriches our lives esthetically. Understanding what produces the colors of a rainbow helps us to see the rainbow in more detail and to see the other, more subtle, light effects that are associated with rainbows. Understanding waves can help us to produce and appreciate music.

In the final analysis, however, there is no defense (nor, arguably, need for any defense) for the study of physics. The human mind is curious, and physics is the formalized extension of that curiosity. We seek to understand what the world is and where it came from. We seek to understand who we are and where we came from. Physics is the basis of the scientific approach to that study. It is in and of itself fascinating and beautiful. May this book convey some of that intrigue and that beauty.

Happy reading!