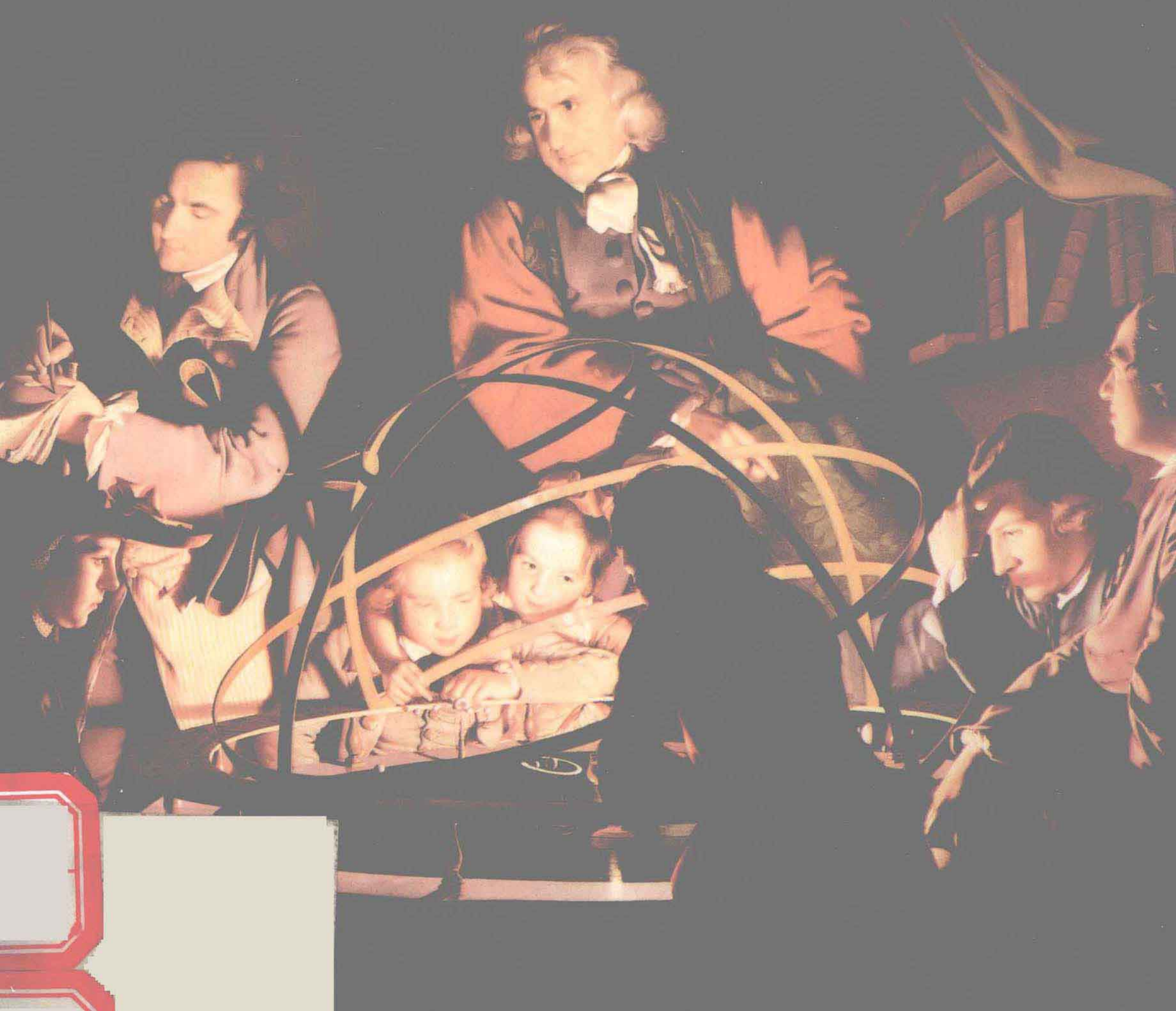
Great Ideas in Physics



ALAN LIGHTMAN

GREAT IDEAS IN PHYSICS

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COVER: "A Philosopher Lecturing on the Orrery" (1766), by English painter Joseph Wright (1734–1797). An orrery is a mechanical model of the solar system. Wright was a member of a group of artists, scientists, and philosophers known as the Lunar Society. Through his paintings, Wright explored the ways in which new developments in science and industry changed man's view of himself and his place in the universe.

GREAT IDEAS IN PHYSICS

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Introduction

Several years ago, I went to Font-de-Gaume, a prehistoric cave in France. The walls inside are adorned with Cro-Magnon paintings done 15,000 years ago, graceful drawings of horses and bison and reindeer. One particular painting I remember vividly. Two reindeer face each other, antlers touching. The two figures are perfect, and a single, loose flowing line joins them both, blending them into one. The light was dim, and the colors had faded, but I was spellbound.

Likewise, I am spellbound by the plays of Shakespeare. And I am spellbound by the second law of thermodynamics. The great ideas in science, like the Cro-Magnon paintings and the plays of Shakespeare, are part of our cultural heritage.

A painter paints a sunset, and a scientist measures the scattering of light. The beauty of nature lies in its logic as well as appearance. And we delight in that logic: The square of the orbital period of each planet equals the cube of its distance from the sun; the shape of a raindrop is spherical, to minimize the area of its surface. Why it is that nature should be logical is the greatest mystery of science. But it is a wonderful mystery.

Discoveries in science are not just about nature. They are about people as well. After Copernicus, we have taken a more humble view of our place in the cosmos. After Darwin, we have recognized new relatives clinging to the family tree. The great ideas of science have changed our view of the world and of ourselves. Science is a human activity as well as an exploration of nature, and, as a human activity, science connects to philosophy, history, literature, and art.

These, then, are the two aims of this book: to provide a grasp of the nature of science, and to explore the connections between science and the humanities. Our exemplary science will be physics.

No attempt has been made to provide a survey of all physics. Instead, this book has been organized around a small number of *ideas*. The ideas are the conservation of energy, the second law of thermodynamics, the relativity of time (relativity theory), and the wave-particle duality of nature (quantum theory). Each of these landmark ideas has changed our world view. Each has had impact and application far beyond science. The law of the conservation of energy, which deals with an indestructible property of nature, provides a fundamental example of the logic and predictive power of science. The second law of thermodynamics, which states that all isolated physical systems unavoidably become more disordered in time, explains why machines cannot keep running forever. The relativity of time, Einstein's discovery, states that time does not flow at an absolute rate, as it seems, but depends on the motion of the clock or observer. Relativity theory shows that our instincts about nature may sometimes be wrong. The quantum theory, which states that objects behave as if they were in two places at once, requires a new conception of reality.

In discussing the physical world, we will learn something of the scientific method. Most science uses inductive reasoning: the scientist makes a number of observations of nature, finds a pattern, generalizes the pattern into a "law" or organizing principle, and then tests that law against future experiments. The discovery of the law of the conservation of energy is an example of inductive science. Deductive science is more rare. Here, the scientist begins by postulating certain truths of nature, with little guidance from outside experiment, and deduces the consequences of those postulates. The consequences are cast into predictions, which can then be pitted against experiment. The theory of relativity is an example of deductive science. Both inductive and deductive reasoning in science are "scientific" in that theories are ultimately judged by their agreement or disagreement with experiment.

In discussing the physical world, we will also encounter a number of approximations and simple models of nature: collisions between balls on frictionless tables, pendulums swinging in three-molecule gases, and so on. Approximations and models are crucial to science. A scientific model begins with a real physical object or system, replaces the original object with a simpler object, and then represents the simplified object with equations describing its behavior. Like a toy boat, a scientific model is a scaled-down version of a physical system, missing some parts of the original. Deciding what parts should be left out requires judgment and skill. The omission of essential features makes the model worthless. On the other hand, if nothing is left out, no simplification has been made and the situation is often too difficult to analyze. In making a model of a swinging pendulum, for example, we might at first try to include the detailed shape of the weight at the end, the density and pressure of the air in the room, and so on. Finding such a description much too complex to manage, we could approximate the weight by a round ball and neglect the air completely. This much simpler system behaves much more like the original. But if we left out gravity, the resulting theoretical pendulum would not swing back and forth. By solving the equations of a model, predictions can be made about the original physical system and then tested.

Alas, the equations. The language of science is mathematics, and it is impossible to appreciate science without equations and quantitative problems.

(I will discuss the role of mathematics in science in the first chapter, in the section on gravitational energy.) Quantitative problems and solutions are scattered throughout the text. However, only high school mathematics, without calculus, is required. An Appendix reviews all of the math you will need. The equations and problems may seem demanding and tedious, but they are well worth the effort. You will not find a watered-down treatment of science in this book. If you invest the time, you will get the real thing.

The other dimension of the book is the humanistic. The relationship between science and the humanities is two-way. Science changes our view of the world and our place in it. In the other direction, the humanities provide the store of ideas and images and language available to us in understanding the world. The exploding star of A.D. 1054, the Crab Nebula, was sighted and documented by the Chinese, but nowhere mentioned in the West, where the Aristotelian notion of the immortality of stars still held sway. We often do not see what we do not expect to see.

The humanistic sources and effects of the ideas in this book are suggested by readings and excerpts from the original scientific literature and from history, literature, philosophy, and art. For example, readings from the early Roman poet Lucretius show the psychological comfort brought by a conservation law; readings from historian Henry Adams show his attempt to apply the second law of thermodynamics to an understanding of the decline of human civilization; readings from Einstein's autobiography show the influence of the philosopher David Hume on Einstein's formulation of the theory of relativity; excerpts from a novel by Vladimir Nabokov illustrate the use of ideas from relativity in literature; readings from the philosopher Ernst Cassirer consider the implications of quantum physics for human ethics.

The humanities excerpts in the text are brief, by necessity, and should be considered only as starting points for further reading. Furthermore, I have taken a rather conservative approach in discussing the humanities. I have included only those excerpts and references that show a direct connection to science. In fact, many of the important connections are indirect and diffuse. New ideas in science, literature, philosophy, and art are often part of a broad change in thinking about the world, and it is impossible to identify that change with a single phrase, such as "the relativity of time," or to decide where an idea started. Nevertheless, I have stuck to examples where the connections between ideas in science and in the humanities are clear and explicit. It seems good to start with examples we can be sure about and then build on those.

Discussion questions will challenge you to think broadly about the ideas and to relate the science to your own interests. The discussion questions are not answered to avoid oversimplification and to allow you to ponder the issues without restraint.

The material in each chapter includes a treatment of the scientific content of the idea, with demonstrations and activities where possible; quantitative problems with solutions; a reading list from the humanities and from the original scientific literature; excerpts from these readings; and discussion questions probing the human dimensions and applications of the ideas. Experiments with nature and a first-hand experience with the scientific method are critical elements of any study of science, and a separate laboratory is included in the course.

For The Instructor

Recent national studies have uncovered a startling illiteracy in science, and new approaches to the teaching of science seem to be called for. This is such an attempt—an interdisciplinary course in science for the nonscience major, centered on a small number of ideas.

Several concerns have determined the style of the book. The material should be accessible to the student with little science background, while preserving the depth and integrity of the subject. To this end, care has been taken to reduce each idea to its essentials, with minimum terminology, and to use only high school mathematics, without calculus. Given these limitations, the essentials are treated with rigor. The emphasis is placed on concepts rather than facts, and the science connects to the body of knowledge and orientation of the nonscience student, a connection not usually made in traditional courses. Finally, each concept should be developed in enough detail so that a solid understanding emerges, with perhaps a new, self-consistent model of the world. This requirement, by necessity, limits the course to a small number of ideas, as opposed to the array of many topics found in a survey course.

The course develops only those concepts needed to understand the four central ideas treated. Many standard concepts in physics, such as the concept of force and the entire field of electricity and magnetism, have been largely omitted.

The book is designed for a one-semester course, with roughly 4 weeks on each chapter. Such a course might alternate science lectures with discussion sessions on the readings, giving equal time to each.

The discussion questions throughout the text are intended for open classroom discussion as opposed to formal lectures. Some of the discussion questions can also be used for essay assignments. In most cases, I have provided little of my own commentary on the excerpts and leave the interpretations and connections to be drawn out of the discussion questions. In the few cases where I do give a brief commentary, my comments should not be taken as gospel. It would be best for students to read the complete works from which the excerpts are taken, as time permits.

The problems and solutions scattered throughout the text are intended not as homework, but as amplifications of the text and as examples of quantitative applications of the ideas. These problems vary greatly in difficulty, and