

Great Ideas in Physics



ALAN LIGHTMAN

GREAT IDEAS IN PHYSICS

Alan Lightman

McGRAW-HILL, INC.

New York St. Louis San Francisco
Auckland Bogotá Caracas Lisbon
London Madrid Mexico Milan Montreal
New Delhi Paris San Juan Singapore
Sydney Tokyo Toronto

GREAT IDEAS IN PHYSICS

Copyright © 1992 by Alan Lightman. All rights reserved. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher.

2 3 4 5 6 7 8 9 0 DOC DOC 9 0 9 8 7 6 5 4 3 2

ISBN 0-07-037935-1 (hard cover)

ISBN 0-07-037937-8 (soft cover)

This book was set in Palatino by The Clarinda Company.
The editors were Susan J. Tubb and Jack Maisel;
the production supervisor was Annette Mayeski.
The cover was designed by Joan Greenfield.
R. R. Donnelley & Sons Company was printer and binder.

Library of Congress Cataloging-in-Publication Data

Lightman, Alan P., (date).

Great ideas in physics / Alan Lightman.

p. cm.

ISBN 0-07-037935-1 (hard cover)—ISBN 0-07-037937-8 (soft cover)

1. Physics. I. Title.

QC21.2.L54 1992

530—dc20

91-27027

GREAT IDEAS IN PHYSICS

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

Contents

Excerpts *ix*

INTRODUCTION 1

CHAPTER 1 THE CONSERVATION OF ENERGY 6

Julius Robert Mayer 6

A Conservation Laws 8

B Gravitational Energy 10

1. A Demonstration with an Inclined Plane 10
2. The Rule for Measuring Gravitational Energy 14
3. A Mental Experiment 17
4. The Role of Mathematics in Science 19

C Kinetic Energy 21

1. Energy of Motion 21
2. The Rule for Counting Kinetic Energy 22
3. Systems with Only Kinetic Energy 28

D Units of Length, Mass, Weight, and Energy 31

E Conservation Laws and Human Freedom 33

F Heat Energy 36

1. Friction and a New Form of Energy 36
2. The Nature of Heat 37
3. Measuring Heat: Temperature 40
4. Units of Heat 42

5.	Heat and the Conservation of Energy	44
6.	Heat, Work, and the First Law of Thermodynamics	50
G	The Conservation of Energy and the Limited Lifetime of the World	52
H	Reactions to Possible Violations of the Conservation of Energy	53

CHAPTER 2 THE SECOND LAW OF THERMODYNAMICS 56

William Thomson 56

A	Reversible and Irreversible Phenomena	58
B	States of a System and Probability of Configurations	60
1.	An Introduction to Probability Theory	60
2.	A Pendulum in Air	63
3.	Evolution to More Probable Configurations	68
4.	Behavior of Realistic Systems with Large Numbers of Molecules	72
5.	The Direction of Time	73
C	Mechanical Energy and Heat	74
D	The Irreversible Flow of Heat	76
E	Doing Work with Heat	79
1.	The Limited Ability to Do Work with Heat and the Universal Decrease of Usable Energy	79
2.	The Efficiency of Machines	81
F	Entropy and Order	89
1.	Entropy	89
2.	Order	90
G	Resistance to the Implications of the Second Law	93
H	The Second Law Applied to Human Society	98
I	The Second Law Used to Refute the Theory of Evolution	104

CHAPTER 3 THE RELATIVITY OF TIME 107

Albert Einstein 107

A	Relativity in Brief	110
B	Science Leading to the Theory of Relativity	112
1.	The Relativity of Mechanics	113
2.	The Relativity of Electricity and Magnetism	113
3.	The Discovery of Light as an Electromagnetic Phenomenon	116
4.	The Michelson-Morley Experiment	118

C	The Theory of Relativity	124
1.	Einstein's Postulates	124
2.	Consequences of Einstein's Postulates: The Strange Law for Combining Speeds	125
3.	Consequences of Einstein's Postulates: The Banishment of Absolute Simultaneity	129
4.	Quantitative Derivation of Time Dilation	132
5.	Experimental Test of Time Dilation: The Disintegration of the Muon	142
6.	Length Contraction	145
7.	Mass-Energy Relation $E_o = mc^2$	149
8.	Meaning of the Speed of Light	151
D	Abolition of Absolute Space and Time	152
1.	Aristotle's View of Space and Motion	152
2.	Newton's View of Space and Time	153
3.	Kant's View of Space and Time	154
E	Einstein's Approach to Science	156
1.	Scientific Postulates as "Free Inventions" of the Human Mind	156
2.	Deductive versus Inductive Thinking and the Influence of Hume on Einstein	158
F	The Influence of the Theory of Relativity on Literature	161
G	Relativity and Sculpture	163

CHAPTER 4 THE WAVE-PARTICLE DUALITY OF NATURE 167

Werner Heisenberg 167

A	Waves	170
1.	Definition of a Wave	170
2.	Properties of Waves: Wavelength, Frequency, Speed, and Amplitude	170
3.	Interference of Waves	172
4.	Nonlocality of Waves	173
5.	Light as a Wave	174
B	The Photoelectric Effect	174
1.	The Nature of the Electron	174
2.	Discovery of the Photoelectric Effect	176
3.	Einstein's Photon Theory of Light	178
4.	Verification of the Photon Nature of Light	182
C	The Double-Slit Experiment	183
1.	Description of the Experiment	183

	2. Experimental Confirmation of the Double-Slit Experiment	187
D	The Role of the Observer and the Nature of Reality	189
	1. The Split between Observer and Observed in Pre-Quantum Physics	189
	2. Interpretations of the Wave-Particle Duality of Nature	189
	3. Berkeley's Views on External Reality	189
E	Quantum Physics and Language	193
F	The Heisenberg Uncertainty Principle and the Demise of Determinism in Science	194
	1. Determinism in Prequantum Physics	194
	2. The Basic Idea of the Principle	196
	3. Spreading out of Light as a Wave	197
	4. Spreading out of Light as a Particle: Components of Velocity and Momentum	206
	5. The de Broglie Relation	210
	6. The Heisenberg Uncertainty Principle	212
	7. Quantum Mechanics	221
G	Determinism, Causality, and Choice in the Quantum World	221
	1. Einstein's View of Quantum Mechanics	221
	2. Causality	222
	3. Determinism, Free Will, and Ethics	223

LABORATORY 227

Appendix A A Review of Some Basic Mathematics 229

1. Numbers and Scientific Notation 229
2. Exponents 230
3. Equations 232
4. The Quadratic Formula 234
5. Geometry 236

Appendix B The Second Law of Thermodynamics and the Behavior of Systems with Large Numbers of Molecules 239

1. The Number of States for a Gas of Many Molecules 239
2. Behavior of a Pendulum in a Realistic Gas 241
3. Heat Flow and Equalization of Temperature in Realistic Systems 243

Excerpts

Alexander Pope, Poem Showing Order in Nature	8
Descartes, Section of <i>Principles</i> Showing Relation between God and Conservation Laws	30
Lucretius, Section of <i>De Rerum Natura</i> Showing Reasons for Postulating the Conservation of Atoms	34
Count Rumford, on the Discovery That Heat Is Motion	38
Julius Mayer, on the Conservation of Energy	47
James Joule, on the Conservation of Energy	48
Niels Bohr, on Giving Up Conservation of Energy to Explain Beta Decay	54
Ernest Rutherford, on Holding onto the Conservation of Energy	55
Lord Kelvin, on a Statement of the Second Law of Thermodynamics	59
Sadi Carnot, on the Importance of Heat Engines and the Question of Their Maximum Efficiency	81
Rudolph Clausius, on the First and Second Laws of Thermodynamics and Application to the Universe as a Whole	90
Lord Kelvin, on Inapplicability of Second Law to Universe as a Whole	94
Arthur Holmes from <i>Age of the Earth</i> , on Desire for Perpetual Motion in Nature	95
Robert Millikan, on Cosmic Rays and Their Proof of a Steady State Universe	97

George Gray, from <i>Atlantic Monthly</i> , on a Nonstatic Cosmos	97
Henry Adams, from <i>Degradation of the Democratic Dogma</i> , Application of Second Law to Understanding Disintegration of Human Society	99
Thomas Pynchon, <i>Crying of Lot 49</i> , in Which Second Law Is Invoked	102
Henry Morris, <i>Troubled Waters of Evolution</i> , on Second Law Used to Refute the Theory of Evolution	104
Edgar Allen Poe, <i>The Bells</i> , Used to Show Common Understanding of Time	109
Albert Einstein, from His Autobiographical Notes, Discussing His Rejection of Authority	112
Albert Einstein, from His 1905 Paper, Discussing the Motivation for Relativity and the Postulates of His Theory of Relativity	124
Aristotle, <i>On the Heavens</i> , on Space and Absolute Motion	153
Isaac Newton, <i>Principia</i> , on Absolute Time and Space	153
Immanuel Kant, <i>Critique of Pure Reason</i> , on Nature and Reality of Time and Space	154
Albert Einstein, on Inductive versus Deductive Reasoning in Science	156
Albert Einstein, Autobiographical Notes, on Error in Kant's Conception of Time and Space and on His Own Thinking about Time and Space	156
Albert Einstein, Autobiographical Notes, on Space and Time and Physics	157
Albert Einstein, Autobiographical Notes, on the Important Influence of Hume on His Thinking in the Development of Relativity	159
David Hume, <i>An Enquiry Concerning the Human Understanding</i> , on Fallacy of Reasoning Only from Direct Experience	160
Vladimir Nabokov, <i>Ada</i> , References to Time and Relativity Theory	161
Jorge Luis Borges, "The Garden of the Forking Paths," References to Nonabsolute Nature of Time	162
Robert Morris, on Role of Time in Modern Sculpture	164
Athena Tacha, on the Use of Relativity and Other Modern Ideas in Physics in Her Sculptures	164
Richard Serra, on the Role of Time, Space, and Motion in His Sculptures	164
Niels Bohr, on the Problem of Inadequate Language to Discuss Quantum Phenomena	169

George Berkeley, <i>Three Dialogues</i> , on Whether Reality Exists Independent of the Human Perception of It	190
Werner Heisenberg, <i>Physics and Philosophy</i> , on Language and Classical Physics	193
Louis de Broglie, Nobel Prize Address, on the Wave Nature of Matter	211
Albert Einstein, on His Dislike of Uncertainty in Nature	221
Milic Capek, on the Inability to Define a "State of the World" after Quantum Mechanics	222
Ernst Cassirer, on Quantum Theory, Choice, and Ethics	223
Selig Hecht, on Quantum Theory, Free Will and Determinism	224

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