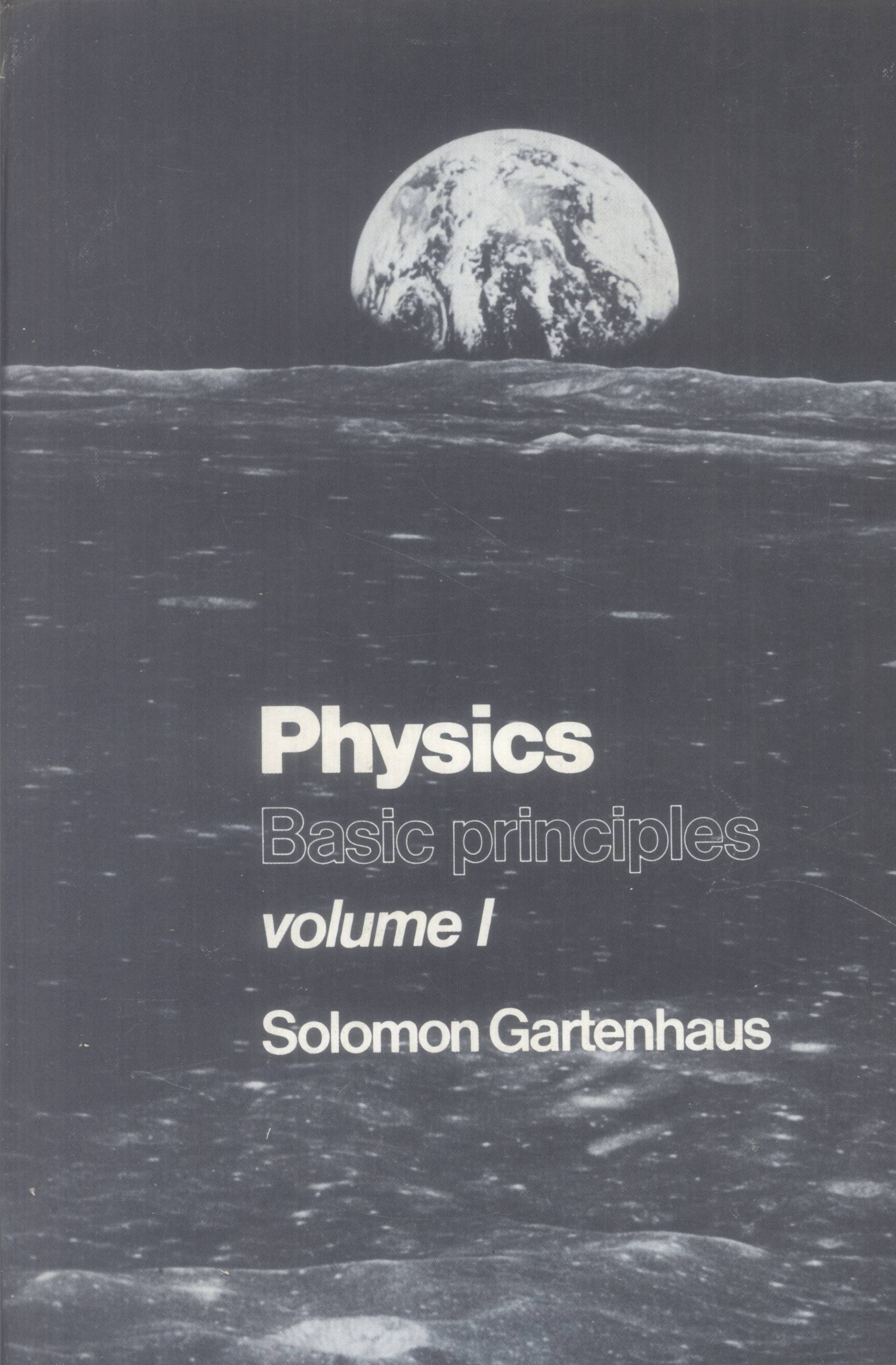

Physics

Basic principles

volume I

Solomon Gartenhaus

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PHYSICAL CONSTANTS

(See Appendix J for more precise values)

	Symbol	Value
Gravitational constant	G	6.67×10^{-11} N-m^2/kg^2
Acceleration of gravity	g	9.81 m/s^2
Avogadro's number	N_0	6.02×10^{23} atoms/mole
Gas constant	R	8.31 J/mole-K = 1.99 cal/mole-K
Boltzmann's constant	k	1.38×10^{-23} J/K
Triple point of water	T_t	273.16 K
Electron mass	m_e	9.11×10^{-31} kg
Proton mass	m_p	1.67×10^{-27} kg
Quantum of electric charge	e	1.60×10^{-19} C
Permeability of free space	μ_0	$4\pi \times 10^{-7}$ H/m
Permittivity of free space	ϵ_0	8.85×10^{-12} F/m
	$\frac{1}{4\pi\epsilon_0}$	8.99×10^9 m/F
Planck's constant	h	6.63×10^{-34} J-s
Speed of light	c	3.00×10^8 m/s
Bohr radius	a_0	5.29×10^{-11} m
Electron Compton wavelength	$\frac{h}{m_e c}$	2.43×10^{-12} m

PHYSICAL DATA

Sun

Mass	1.99×10^{30} kg
Mean radius	6.96×10^{8} m
Mean surface temperature	5800 K
Mean density	1.410×10^{3} kg/m^3

Earth

Mass	5.98×10^{24} kg
Mean radius	6.37×10^{6} m
Mean distance from sun	1.496×10^{11} m
Mean orbital speed	29.8 km/s
Mean density	5.517×10^{3} kg/m^3

Moon

Mass	7.35×10^{22} kg
Mean radius	1.738×10^{6} m
Mean distance from earth	3.844×10^{8} m
Mean density	3.342×10^{3} kg/m^3

Terrestial

Atmospheric pressure (at sea level and 0°C)	76 cm Hg, 1.013×10^{5} N/m^2
Mass density of air (at sea level and 0°C)	1.293 kg/m^3
Mass density of water (at sea level and 0°C)	1.000×10^{3} kg/m^3
Mean molecular weight of dry air	29.0

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Physics
Basic principles

Without my work in natural science I should never have known human beings as they really are. In no other activity can one come so close to direct perception and clear thought or realize so fully the error of the senses, the mistakes of the intellect, the weakness and greatness of the human character.

GOETHE

[redacted]

To Johanna

Preface

This is Volume I of a two volume text designed for a one-year introductory physics course for students of science and engineering. Approximately two thirds of this volume (Chapters 2–12) is devoted to mechanics; the remainder deals with kinetic theory, heat, and thermodynamics (Chapters 13–17) and with wave motion (Chapter 18). The companion Volume II treats electromagnetism (Chapters 19–29) and optics (Chapters 30–33) and concludes with an introductory chapter on quantum phenomena.

Although most of the subject matter of both volumes deals with the laws and the phenomena of classical physics, a substantial number of references to, and illustrations of, nonclassical phenomena have been distributed throughout the text. These are intended to give the student some feeling for recent developments, as well as to alert him to the limitations of certain of the classical laws, and of the seemingly universal applicability of others. Thus, he sees the ideas of the conservation of energy and of momentum applied not only to laboratory-sized bodies, but to the motions and the interactions of nuclear, atomic, planetary, and stellar systems as well. In addition, a number of chapters contain optional sections (marked by a dagger †), which generalize or extend the text material in some way or describe related but more recent discoveries. For example, Chapter 1 includes a qualitative description of nuclei and of subnuclear particles, and in Chapter 19 the charge structure of the neutron and the proton is briefly discussed. Other material of this nature includes discussions of: the Lorentz transformation, as the high velocity generalization of the Galilean transformation (Section †3–12); the relativistic forms of the laws of energy and momentum conservation (Section †9–10); and Einstein's equivalence principle and the bending of light rays in a gravitational field (Section †5–9).

To a considerable extent, this book reflects my view that the student for whom the book is intended is preparing for a career for which some in-depth knowledge of physics is essential. With today's accelerating tempo of scientific discovery and technological innovation foremost in mind, I have endeavored, throughout the text, to emphasize the basic physical laws and to present them in as succinct and complete a manner as it is possible to do at the introductory level. Included therefore are not only extensive discussions of the scope of the laws and their interrelations but, where appropriate, their ranges of validity as well. By placing the focus on the basic physical laws in this way, it is hoped that the student will come to understand some of the physicists' empirical-logical approach to the world and will acquire thereby a realistic perception of these laws and a secure intellectual base from which to pursue further studies.

Specific features of the book which are directed toward implementing this approach include:

1. All basic physical laws, such as Newton's laws of motion, Coulomb's law, and Faraday's law, are first introduced by use of certain conceptually simple and easily visualized experiments. The laws themselves are then abstracted from these experiments and reformulated in quantitative mathematical terms. Finally, the important features of the laws and their relation with other laws are brought out and reinforced in the student's mind by applying them to a variety of physical situations.
2. Because of their conceptual importance, both as a starting point in physical reasoning and as a tool for codifying diverse physical phenomena, the various conservation laws receive particularly heavy emphasis. More than a third of the material on mechanics, for example, deals with these laws. Extensive discussions of these laws are presented and the student is able to see, at several levels, their connection with other physical laws, their interrelations, and their limits of validity.
3. Wherever appropriate, all physical quantities are first introduced by use of operational definitions. My view here is that in the student's subsequent capacity as a professional he may well be called upon to apply physical laws in regions bordering on their limits of validity. Therefore, he should be able to reexamine critically and systematically all basic definitions and physical laws in light of their underlying assumptions and for this purpose operational definitions are indispensable.

4. A considerable effort has been made to present the material in a way to make it dovetail more closely with that found in more advanced courses. Thus, the language, the basic approach, and the attitude, but not the level, are those found more often in texts at the intermediate and higher level.

Some other features of the book are:

1. As is traditional in introductory physics courses of this type, it is assumed that the student is taking concurrently a course in calculus. Nevertheless, many of the basic ideas of the differential and the integral calculus are introduced as needed and integrated with the text. Detailed derivations, however, are usually relegated to one of the brief mathematical appendices. Vectors are introduced in Chapter 3 and used throughout the text. The dot product is defined in Chapter 7 and the cross product in Chapter 10.
2. Each chapter contains a wide selection of *questions* and *problems*. The more difficult problems have been marked by an asterisk (*) and those which require some knowledge of material covered in optional sections have been similarly marked by a dagger (†). As a general rule, the order of the problems follows closely the ordering of the text material. The questions generally call for answers of a qualitative or semiquantitative nature, and are intended mainly to help the student test his physical understanding of the text material. Also included are some questions whose main purpose is to be thought provoking.
3. A sizable number of worked examples (averaging more than ten per chapter) are distributed throughout the text. These span all levels of difficulty, from the simple formula-substitution type to the more complex ones whose purpose is to extend some aspect of a topic treated in the text. Also, many of these examples serve as models which the student can use as an aid in problem solving.
4. The SI or International System of Units (often called the metric or the MKSA system) is used exclusively throughout the text. Included, however, are definitions of and conversion tables to the CGS and the English system of units. With only rare exception the answers to all problems and worked examples that call for a numerical value are in metric units.
5. A broad spectrum of applications has been included in the text. Thus there is available considerable latitude in adapting it to courses of varying length or specialized needs.

In writing this book, I have received help in many forms and from many more sources than it is possible to acknowledge individually. I should like to thank particularly Orland E. Johnson who has been a valuable source of advice on all aspects of the book throughout the long years of writing. I am also greatly indebted to David J. Ennis and Nicholas J. Giordano, who with

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skill and patience worked out solutions to all problems and were helpful in a variety of other ways; to John J. Brehm, Gary S. Kovener, Earl W. McDaniel and Walter W. Wilson, who critically reviewed the manuscript and made many valuable suggestions; to the many of my colleagues at Purdue, particularly Edward Akely, Irving Geib, Don Schleuter, and Isadore Walerstein for much encouragement and for help when needed; and to the members of the editorial staff at Holt, Rinehart and Winston, Inc., through whose patience, persistence, and labors this book ultimately came into being. Finally, I should like to thank Debbie Carr, Coleen Flanagan, and my wife Johanna for their invaluable secretarial assistance and my sons Mike and Kevin for their help with the galleys.

Solomon Gartenhaus
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October 1974

APPENDIX A Differentiation formulas

The purpose of this appendix is to list for reference purposes a number of formulas that are useful in calculating derivatives.

Let $x(t)$, $x_1(t)$, and $x_2(t)$ represent functions of the independent variable t, and let α be a constant independent of time and n a positive integer. Then

$$\frac{d}{dt}(\alpha t^n) = n\alpha t^{n-1} \tag{A-1}$$

$$\frac{d}{dt}[x_1(t) + \alpha x_2(t)] = \frac{dx_1}{dt} + \alpha \frac{dx_2}{dt} \tag{A-2}$$

$$\frac{d}{dt}[x_1(t)x_2(t)] = x_1 \frac{dx_2}{dt} + x_2 \frac{dx_1}{dt} \tag{A-3}$$

$$\frac{d}{dt} f(x(t)) = \frac{df}{dx}\frac{dx}{dt} \tag{A-4}$$

where, in (A-4), f is a function of the independent variable t only through its explicit dependency on the function $x(t)$. The relation in (A-4) is known as the *chain rule.*

To give some idea as to how these results are obtained, let us derive (A-1). Applying the definition of a derivative

$$\frac{dx}{dt} = \lim_{\Delta t \to 0} \frac{x(t + \Delta t) - x(t)}{\Delta t}$$

to the function $x = \alpha t^n$, we obtain

$$\frac{d}{dt}(\alpha t^n) = \lim_{\Delta t \to 0} \frac{\alpha(t + \Delta t)^n - \alpha t^n}{\Delta t}$$

By use of the binomial expansion

$$(a+b)^n = a^n + na^{n-1}b + \frac{n(n-1)}{2!}a^{n-2}b^2 + \cdots + b^n$$

and the fact that n is a positive integer, this may be simplified to the desired result:

$$\frac{d(\alpha t^n)}{dt} = \lim_{\Delta t \to 0} \alpha \frac{t^n + nt^{n-1}\Delta t + \cdots + (\Delta t)^n - t^n}{\Delta t}$$

$$= \alpha n t^{n-1}$$

More generally, it can be shown that (A-1) is valid for n any positive or negative number.

The validity of (A-2), (A-3), and (A-4) and related formulas may be established in a similar way.

APPENDIX B Planetary data

Planet	*Radius* (10^3 km)	*Radius* (earth = 1)	*Distance from sun* (10^6 km)	*Mass* (5.98×10^{24} kg)	*Density* (10^3 kg/m^3)	*Rotation period* (sideral)	*Period* (years)
Mercury	2.4	0.38	58	0.06	5.4	59^d	0.24
Venus	6.1	0.95	108	0.82	5.3	243^d	0.62
Earth	6.37	1.00	150	1.00	5.5	$23^h56^m04^s$	1.00
Mars	3.39	0.53	228	0.11	3.94	$24^h37^m23^s$	1.88
Jupiter	70	11.0	778	318	1.33	9^h55^m	11.9
Saturn	58	9.1	1426	95	0.70	10^h38^m	29.5
Uranus	24	3.7	2869	14.5	1.56	10^h49^m	84
Neptune	25	3.5	4495	17.2	2.27	16^h(?)	165
Pluto	6.0	0.46(?)	5900	0.06(?)	?	6.4^d(?)	248

The sun: Mass, 330,000 $M_\oplus = 1.99 \times 10^{30}$ kg; mean radius, 6.95×10^5 km; mean density, 1.42×10^3 kg/m^3

The moon: Mass, .0123 $M_\oplus$; mean radius, 1.74×10^3 km; mean density, 3.36×10^3 kg/m^3; mean distance from earth, 3.8×10^5 km

The earth: $M_\oplus = 5.98 \times 10^{24}$ kg; mean radius, 6.35×10^3 km; mean density, 5.5×10^3 kg/m^3

APPENDIX C The derivatives of the sine and the cosine

The purpose of this appendix is to derive the rules for differentiating the sine and the cosine functions. To this end, let us first establish the limit

$$\lim_{\theta \to 0} \frac{\sin \theta}{\theta} = 1 \qquad \textbf{(C-1)}$$

where the angle θ is expressed in radians. The fact that for sufficiently small angles, $\theta \cong \sin \theta$ is easily established by reference to a table of trigonometric functions. Expressing θ in radians we find the values $\sin 0.10 = 0.09983$, $\sin 0.05 = 0.04998$, $\sin 0.01 = 0.01000$, and, more generally, for $\theta \leqslant 0.10$ rad ($\cong 6°$) we find that θ and $\sin \theta$ differ from each other by less than 1 percent.

To establish the validity of (C-1), consider in Figure C-1 a circle of radius R centered at A, and let AB and AC be two radii subtending an angle θ. Construct from the point B the line BE tangent to the circle at B and the line BD to be perpendicular to AC. The angle between BD and BE is also θ. By

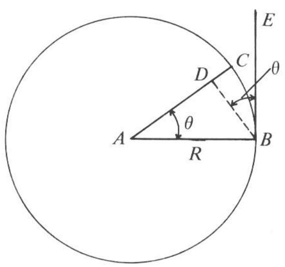

Figure C-1

definition of a radian, the length of the arc BC is $R\theta$ and thus

$$\theta = \frac{\text{arc } BC}{R}$$

Further, in the right triangle ABD,

$$\sin\theta = \frac{BD}{R}$$

and thus by division we find that

$$\frac{\sin\theta}{\theta} = \frac{BD}{\text{arc } BC}$$

In the limit as $\theta \to 0$, since BD becomes parallel to BE, it follows that the length of BD must become more and more equal to the arc BC. The validity of (C-1) is thus established.

We shall now use (C-1) to calculate the derivative of $\sin\theta$. According to the definition of a derivative, we have

$$\begin{aligned}\frac{d}{d\theta}\sin\theta &= \lim_{\Delta\theta\to 0}\frac{\sin(\theta+\Delta\theta)-\sin\theta}{\Delta\theta}\\ &= \lim_{\Delta\theta\to 0}\frac{\sin\theta\cos\Delta\theta+\sin\Delta\theta\cos\theta-\sin\theta}{\Delta\theta}\end{aligned} \tag{C-2}$$

where the second equality follows by use of the identity

$$\sin(A+B) = \sin A\cos B + \cos A\sin B$$

Since $\cos 0 = 1$, it follows that for small $\Delta\theta$, $\cos\Delta\theta \cong 1$. Hence (C-2) becomes

$$\begin{aligned}\frac{d}{d\theta}\sin\theta &= \lim_{\Delta\theta\to 0}\frac{\cos\theta\sin\Delta\theta}{\Delta\theta}\\ &= \cos\theta\end{aligned} \tag{C-3}$$

where the second equality follows by use of (C-1).

Similarly, the derivative of the cosine is found to be

$$\begin{aligned}\frac{d}{d\theta}\cos\theta &= \lim_{\Delta\theta\to 0}\frac{\cos(\theta+\Delta\theta)-\cos\theta}{\Delta\theta}\\ &= \lim_{\Delta\theta\to 0}\frac{\cos\theta\cos\Delta\theta-\sin\theta\sin\Delta\theta-\cos\theta}{\Delta\theta}\\ &= \lim_{\Delta\theta\to 0}\frac{-\sin\theta\sin\Delta\theta}{\Delta\theta}\\ &= -\sin\theta\end{aligned} \tag{C-4}$$

where the second equality follows from the identity

$$\cos(A+B) = \cos A\cos B - \sin A\sin B$$

and the fourth from (C-1).

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