• Expanded discussion of the Lense-Thirring and de Sitter precessions, and the Stanford gyroscope experiment
• The Reissner-Nordström solution
• Black-hole thermodynamics and the Hawking radiation process
• Update on black-hole candidates
• Expanded discussion of observational limits for the matter density in the universe
• Dark Matter
• Recent developments in the determination of the Hubble constant
• COBE results on the cosmic thermal radiation
• Thermal equilibrium of particles in the early universe
• Nucleosynthesis
• Density perturbations and the Jeans mass
• The inflationary model of the universe

The Second Edition also includes expanded reading lists and references. A substantial number of new problems has been added to the chapters.
This new Second Edition of *Gravitation and Spacetime* brings a widely acclaimed and successful text up-to-date with the latest research and findings in gravitation and general relativity theory. Like the previous edition, the text is written to be accessible to students and to convey the excitement of discovery in the field today. *Gravitation and Spacetime*, Second Edition, continues to be the perfect choice for advanced undergraduate and graduate-level courses. Here is a brief list of just some of the new highlights.

- The fifth force and tests for the inverse-square law
- Updates on experimental and observational data for the Eötvös experiment, the deflection of light, the gravitational redshift, the retardation of light, the perihelion precession, etc.
- Differential forms and the exterior calculus in flat and in curved spacetime
- The gravimagnetic field
- Gravitational lenses, with an extensive discussion of theory, observation, and applications
- The Hulse-Taylor pulsar
- Recent developments in the design and construction of detectors of gravitational waves, including interferometric detectors and LIGOS
- Killing vectors and Lie derivatives
- Stable and unstable orbits in the Schwarzschild geometry; accretion disks

(Continued on back flap)
Einstein discovered his theory of gravitation in 1916. By rights, this theory should not have been discovered until twenty years later, when physicists acquired a clear understanding of relativistic field theory and of gauge invariance. Einstein's profound and premature insights into the nature of gravitation had more to do with intuition than with logic. In contrast to the admirably precise and clear operational foundations on which he based his theory of special relativity, the foundations on which he based general relativity were vague and obscure. As has been emphasized by Synge and by Fock, even the very name of the theory indicates a misconception: there is no such thing as a relativity more general than special relativity. But, whatever murky roads he may have taken, in the end Einstein's intuition led him to create a theory of dazzling beauty. If, using Arthur Koestler's image, we regard Copernicus, Kepler, and Newton as sleepwalkers, who knew where they wanted to go and managed to get there without quite knowing how, then Einstein was the greatest sleepwalker of them all.

It is the objective of this book to develop gravitational theory in the most logical and straightforward way—in the way it probably would have developed without Einstein's intervention. This means that we will begin with the linear approximation and regard gravitation as a field theory, entirely analogous to electrodynamics. The geometrical interpretation and the nonlinear Einstein equations gradually emerge as we attempt to understand and improve the equations of the linear approximation. This approach is not new: Gupta, Feynman, Thirring, and Weinberg have presented it from somewhat different points of view and with varying amounts of detail. One advantage of this approach is that it gives a clearer insight into how and why gravitation is geometry. Another advantage is that the linear theory permits us to delve immediately into the physics: light deflection, retardation, redshift, gravitational lensing, and gravitational radiation can be directly treated in the context of the linear approximation, without any lengthy preliminary digressions on the mathematics of Riemannian spacetime geometry.

In this second edition of the book, as in the first, we place considerable emphasis on the description of experimental results. The last thirty years have seen a blossoming of experimental and observational data, and we have tried to make the lists of such results as complete and up-to-date as possible.

All the chapters of the first edition have been drastically revised. On a small scale, this involved corrections of some mistakes and improvements of explanations. On a larger scale, it involved reorgani-
ization and additions. For instance, the linear approximation is now presented in two chapters (Chapter 3 on the theoretical basis, and Chapter 4 on applications), and the early universe has expanded to fill all of the new Chapter 10, which now includes details on the thermal equilibrium of particles in the early universe, on nucleosynthesis, and on the inflationary scenario. Other additions are a broad discussion of the hypothetical deviations from the inverse-square law (including the ill-fated speculations on the "fifth force") in Chapter 1, a thorough treatment of the theoretical and observational aspects of gravitational lenses in Chapter 4, discussion of the Hulse-Taylor pulsar and of laser interferometric gravitational wave detectors (LIGOs) in Chapter 5, details on the geodetic precession of a gyroscope and the Stanford Gravity Probe B experiment in Chapter 7, a semiquantitative treatment of particle creation by black holes (the Hawking process) in Chapter 8, and discussion of the latest determinations of the Hubble constant, dark matter, and the COBE results on the cosmic microwave radiation in Chapter 9.

The language of differential forms and the exterior calculus of Cartan is now widely used in general relativity. New sections added to Chapters 2 and 6 provide self-contained introductions to this language. However, the bulk of the book relies on ordinary tensor calculus, since this is easier to grasp for students in their first encounter with general relativity.

The exercises that are scattered throughout the chapters are an integral part of the text; they amplify discussions, supply proofs, and are intended to be done while the book is being read. Only a fanatic will find the time to do them all; the reader is invited to look upon these exercises as challenges which should not always be refused. The collection of problems at the ends of the chapters that appeared in the first edition has been much expanded, mostly by the addition of problems from examinations that were given to students at Rensselaer Polytechnic Institute.

We thank Charles J. Goebel (University of Wisconsin, Madison), Stuart L. Shapiro (Cornell University), and Lawrence C. Shepley (University of Texas at Austin) for their careful reviews of this second edition, and for their many suggestions for improvements. We also thank our students, upon whom a trial edition of this book was inflicted, for their patience and their comments. One of the authors (H.C.O.) would like to thank the Università di Roma "La Sapienza" and the Specola Vaticana, Castel Gandolfo, for their hospitality during work on this book.

H. C. O.
R. R.

April 1994
Further Reading 173
References 173
Problems 174

4. APPLICATIONS OF THE LINEAR APPROXIMATION 175
4.1 The Field of a Spherical Mass 176
4.2 The Gravitational Time Dilation 179
4.3 The Deflection of Light 188
4.4 The Retardation of Light 196
4.5 Gravitational Lenses 203
4.6 Optics of Gravitational Lenses 213
4.7 The Field of a Rotating Mass; Lense-Thirring Effect 220
Further Reading 228
References 229
Problems 232

5. GRAVITATIONAL WAVES 241
5.1 Plane Waves 242
5.2 The Emission of Gravitational Radiation 252
5.3 Emission by a Vibrating Quadrupole 258
5.4 Emission by a Rotating Quadrupole 262
5.5 Emission of Bursts of Gravitational Radiation 269
5.6 The Quadrupole Detector and Its Cross Section 275
5.7 Experiments with Detectors of Gravitational Radiation 281
Further Reading 295
References 296
Problems 297

6. RIEMANNIAN GEOMETRY 302
6.1 General Coordinates and Tensors 305
6.2 Parallel Transport; the Covariant Derivative 309
6.3 The Geodesic Equation 317
6.4 The Metric Tensor 322
6.5 The Riemann Curvature Tensor 332
6.6 Geodesic Deviation and Tidal Forces 341
6.7 Differential Forms in Curved Space 345
6.8 Isometries of Spacetime; Killing Vectors 352
Further Reading 359
References 361
Problems 361
7. **EINSTEIN’S GRAVITATIONAL THEORY** 370
   7.1 General Covariance and Invariance 371
   7.2 Einstein’s Field Equation 380
   7.3 Another Approach to Einstein’s Equation; the Cosmological Term 385
   7.4 The Schwarzschild Solution 391
   7.5 Birkhoff’s Theorem 397
   7.6 The Motion of Planets; Perihelion Precession 401
   7.7 The Propagation of Light; the Redshift 409
   7.8 Geodetic Precession 414
   7.9 Mach’s Principle 423
Further Reading 426
References 428
Problems 430

8. **BLACK HOLES AND GRAVITATIONAL COLLAPSE** 437
   8.1 Singularities and Pseudosingularities 438
   8.2 The Black Hole and Its Horizon 443
   8.3 The Maximal Schwarzschild Geometry 449
   8.4 The Kerr Solution and the Reissner-Nordström Solution 459
   8.5 Horizons and Singularities in the Rotating Black Hole 464
   8.6 The Maximal Kerr Geometry 472
   8.7 Black-Hole Thermodynamics; the Hawking Process 481
   8.8 Gravitational Collapse and the Formation of Black Holes 489
   8.9 In Search of Black Holes 496
Further Reading 502
References 504
Problems 506

9. **COSMOLOGY** 510
   9.1 The Large-Scale Structure of the Universe 511
   9.2 Cosmic Distances 518
   9.3 The Cosmological Redshift; Hubble’s Law 524
   9.4 The Age of the Universe 531
   9.5 The Cosmic Thermal Radiation 534
   9.6 The Mass Density; Dark Matter 537
   9.7 Comoving Coordinates; the Robertson-Walker Geometry 543