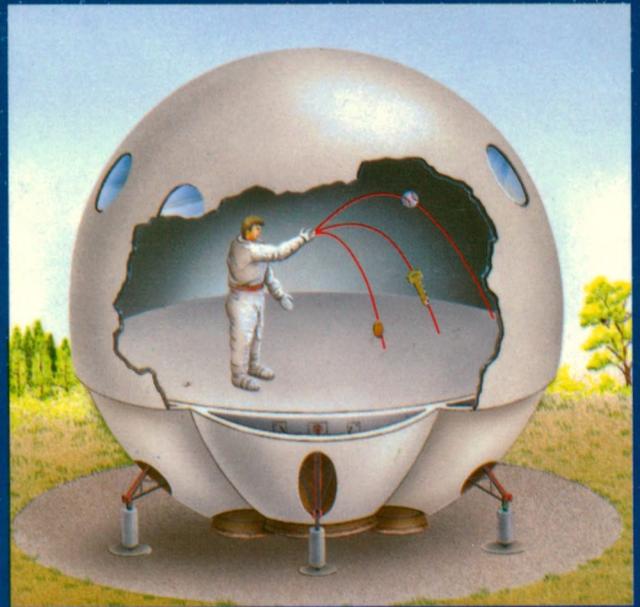
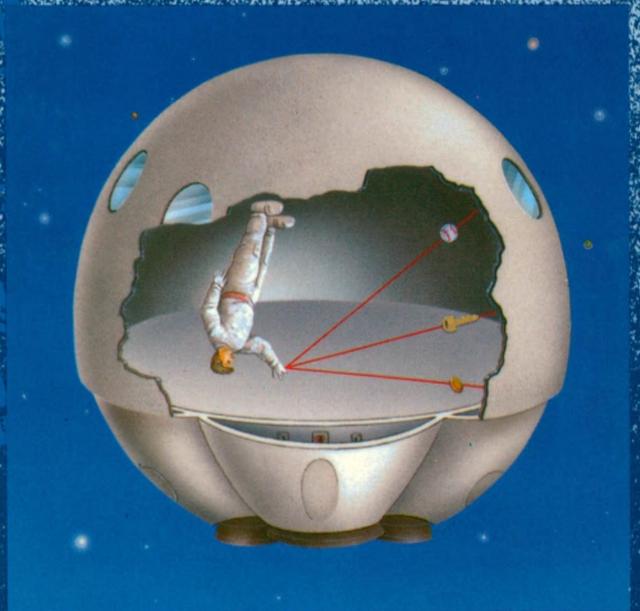


SPACETIME PHYSICS

INTRODUCTION TO SPECIAL RELATIVITY; SECOND EDITION



EDWIN F. TAYLOR
JOHN ARCHIBALD WHEELER

THE UNITY OF SPACETIME

Relativity describes Nature from quark to cosmos. Relativity empowers its user to ponder deeply, to analyze widely, to predict accurately. It is a theory of fantastic innocence, simplicity, and power.

Yet "relativity theory" is a misleading term, a term Albert Einstein avoided for years. True, he recognized and revealed to the world that the time between two events is typically different as recorded by Earth observer or spaceship commander. Time between events is *relative*. Relative too is the distance between events. Yet behind these differences Einstein discerned unity: concepts and quantities on which everyone in the universe agrees. What concepts and quantities?

Events. An explosion is an explosion. A birth is a birth. Whether it is the birth of a star or your own birth, everyone agrees that it happens.

Wristwatch time. Carry a wristwatch directly from one event to a second event, so that both take place at the wristwatch. Or lay a rod between two events that occur at the same time. Everyone correctly predicts the wristwatch reading and this rod length.

The path connecting events. Were you there, at the first event? Yes. And at the second? Yes. And the last? Yes. Does everyone in the universe agree that you were present at every event in this string? Yes. Does everyone agree on the advance of your wristwatch time from event to event along this entire string of events? Yes!

Conservation laws. Everyone agrees that momentum is conserved in a collision of particles. It is also conserved when particles are created, transformed, or annihilated in that collision. Energy, too, is conserved in the same collision, everyone agrees. •

Agreements of these four kinds bear witness to a powerful and simple unity, the unity of space and time: *spacetime!* Special relativity explores the unity of spacetime. General relativity recognizes that spacetime is not just a passive stage on which events occur; spacetime is an actor that takes part in physical events. All of relativity comes in a single simple sentence: *Spacetime grips mass, telling it how to move; and mass grips spacetime, telling it how to curve.*

SPACETIME PHYSICS

introduction to special relativity

Second Edition

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Massachusetts Institute of Technology

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*Princeton University and
University of Texas at Austin*



W. H. Freeman and Company
New York

Library of Congress Cataloging-in-Publication Data

Taylor, Edwin F.

Spacetime physics introduction to special relativity / Edwin F. Taylor, John Archibald Wheeler. — 2nd ed.

p. cm.

Includes bibliographical references and index.

ISBN-13: 978-0-7167-2327-1

ISBN-10: 0-7167-2327-1

1. Special relativity (Physics) I. Wheeler, John Archibald, 1911- . II. Title.

QC173.65T37 1991

530.1'1—dc20

92-722

CIP

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Printed in the United States of America
Eleventh printing

Both males and females make competent observers. We ordinarily treat the laboratory observer as male and the rocket observer as female. Beyond this, to avoid alternating "his" and "her" in a single chapter, we use female pronouns for an otherwise undesignated observer in odd-numbered chapters and male pronouns in even-numbered chapters.

Epigram, facing page: Einstein remark to his assistant Ernst Straus, quoted in *Mainsprings of Scientific Discovery* by Gerald Holton in *The Nature of Scientific Discovery*, Owen Gingerich, Editor (Smithsonian Institution Press, Washington, 1975).

What I'm really interested in is whether God could have made the world in a different way; that is, whether the necessity of logical simplicity leaves any freedom at all.

— Albert Einstein

Edwin F. Taylor and John Archibald Wheeler have written a general relativity sequel to *Spacetime Physics*, namely: *Exploring Black Holes: Introduction to General Relativity* Addison Wesley Longman, San Francisco, 2000
ISBN 0-201-38423-X

CONTENTS

Chapter 1 SPACETIME: OVERVIEW 1

The great unity is spacetime; its measure, the spacetime interval, is the same for all observers.

1.1 Parable of the Surveyors 1 1.2 Surveying Spacetime 5 1.3 Events and Intervals Alone! 9 1.4 Same Unit for Space and Time: Meter, Second, Minute, or Year 11 1.5 Unity of Spacetime 15 References 18
Acknowledgments 19 Introduction to the Exercises 19 Exercises 20

Chapter 2 FLOATING FREE 25

Jump off the roof: On the way down—in free float—we have an (almost!) perfect setting for conducting experiments.

2.1 Floating to the Moon 25 2.2 The Inertial (Free-Float) Frame 26
2.3 Local Character of Free-Float Frame 30 2.4 Regions of Spacetime 34
2.5 Test Particle 36 2.6 Locating Events With a Lattice of Clocks 37
2.7 Observer 39 2.8 Measuring Particle Speed 40 2.9 Rocket
Frame 41 2.10 Summary 43 References 44 Exercises 45

Chapter 3 SAME LAWS FOR ALL 53

Without looking out of the window, we cannot tell which free-float frame we are in.

3.1 The Principle of Relativity 53 3.2 What Is NOT the Same in Different
Frames 56 3.3 What IS the Same in Different Frames 60 3.4 Relativity of
Simultaneity 62 3.5 Lorentz Contraction of Length 63 3.6 Invariance of
Transverse Dimension 65 3.7 Invariance of the Interval Proved 67
3.8 Invariance of the Interval for ALL Free-Float Frames 71 3.9 Summary 73
References 76 Acknowledgments 77 Exercises 78

Special Topic LORENTZ TRANSFORMATION 95

Observe an event in the laboratory; predict its space and time readings in the rocket.

L.1 Lorentz Transformation: Useful or Not? 95 L.2 Faster Than Light? 96
L.3 First Steps 99 L.4 Form of the Lorentz Transformation 100
L.5 Completing the Derivation 101 L.6 Inverse Lorentz
Transformation 102 L.7 Addition of Velocities 103 L.8 Summary 111
Reference 111 Exercises 112

Chapter 4 TRIP TO CANOPUS 121

Travel quickly to a distant star and return, to find we have traveled into the future.

4.1 Invitation to Canopus 121 **4.2** Stripped-Down Free-Float Frame 121
4.3 Faster Than Light? 122 **4.4** All of Space is Ours! 123 **4.5** Flight Plan 124
4.6 Twin Paradox 125 **4.7** Lorentz Contraction 126
4.8 Time Traveler 127 **4.9** Relativity of Simultaneity 128
4.10 Experimental Evidence 131 References 134 Exercises 135

Chapter 5 TREKKING THROUGH SPACETIME 137

Move or stand still; in either case we soar through spacetime.

5.1 Time? No. Spacetime Map? Yes. 137 **5.2** Same Events; Different Free-Float Frames 139
5.3 Invariant Hyperbola 143
5.4 Worldline 143 **5.5** Length Along a Path 147 **5.6** Wristwatch Time Along a Worldline 148
5.7 Kinked Worldline 152 **5.8** Stretch Factor 155
5.9 Touring Spacetime Without a Reference Frame 160
5.10 Summary 162 References 163 Exercises 163

Chapter 6 REGIONS OF SPACETIME 171

The speed of light is a mighty barrier that preserves cause and effect.

6.1 Light Speed: Limit on Causality 171 **6.2** Relation Between Events: Timelike, Spacelike, or Lightlike 172
6.3 Light Cone: Partition in Spacetime 177 Exercises 183

Chapter 7 MOMENERGY 189

A second great unity is momentum-energy (momenergy); its measure, mass, is the same for all observers.

7.1 Momenergy: Total Conserved in a Collision 189 **7.2** Momenergy Arrow 191
7.3 Momenergy Components and Magnitude 195
7.4 Momentum: "Space Part" of Momenergy 199 **7.5** Energy: "Time Part" of Momenergy 201
7.6 Conservation of Momenergy and its Consequences 207
7.7 Summary 211 Acknowledgment 213
Exercises 214

Chapter 8 COLLIDE. CREATE. ANNIHILATE. 221

Convert mass to energy and energy to mass.

8.1 The System 221 **8.2** Three Modest Experiments 222 **8.3** Mass of a System of Particles 224
8.4 Energy Without Mass: Photon 228 **8.5** Photon Used to Create Mass 233
8.6 Material Particle Used to Create Mass 234
8.7 Converting Mass to Usable Energy: Fission, Fusion, Annihilation 237
8.8 Summary 244 **Dialog:** Use and Abuse of the Concept of Mass 246
References 251 Acknowledgments 252 Exercises 253

Chapter 9 GRAVITY: CURVED SPACETIME IN ACTION 275

Gravity is not a force reaching across space but a distortion—curvature!—of spacetime experienced right where you are.

9.1 Gravity in Brief 275 **9.2** Galileo, Newton, and Einstein 275 **9.3** Local Moving Orders for Mass 277 **9.4** Spacetime Curvature 280 **9.5** Parable of the Two Travelers 281 **9.6** Gravitation as Curvature of Spacetime 284
9.7 Gravity Waves 288 **9.8** Black Hole 292 **9.9** The Cosmos 296
References 296

ANSWERS TO ODD-NUMBERED EXERCISES 299

INDEX 303

SELECTED PHYSICAL CONSTANTS

Speed of light in a vacuum	$c = 2.99792458 \times \begin{cases} 10^8 \text{ meters/second} \\ 10^{10} \text{ centimeters/second} \end{cases}$ $c = \begin{cases} 1 \text{ meter of distance/meter of light-travel time} \\ 1 \text{ centimeter of distance/centimeter of light-travel time} \end{cases}$
Gravitational constant	$G = 6.673 \times \begin{cases} 10^{-11} \text{ meter}^3/(\text{kilogram-second}^2) \\ 10^{-8} \text{ centimeter}^3/(\text{gram-second}^2) \end{cases}$
Planck constant	$h = 6.6261 \times \begin{cases} 10^{-34} \text{ kilogram-meter}^2/\text{second} \\ 10^{-27} \text{ gram-centimeter}^2/\text{second} \end{cases}$
Boltzmann constant	$k = 1.38066 \times \begin{cases} 10^{-23} \text{ joule/degree Kelvin} \\ 10^{-16} \text{ erg/degree Kelvin} \end{cases}$
Elementary charge	$e = \begin{cases} 1.60218 \times 10^{-19} \text{ coulombs} \\ 4.80321 \times 10^{-10} \text{ esu or } (\text{gram centimeter}^3/\text{second}^2)^{1/2} \end{cases}$
Electron mass	$m_e = 9.1094 \times \begin{cases} 10^{-31} \text{ kilogram} \\ 10^{-28} \text{ gram} \end{cases}$
Electron rest energy	$m_e c^2 = 8.1871 \times \begin{cases} 10^{-11} \text{ joules} \\ 10^{-7} \text{ ergs} \end{cases}$ $= 0.510999 \text{ MeV}$
Proton mass	$m_p = 1.67262 \times \begin{cases} 10^{-27} \text{ kilogram} \\ 10^{-24} \text{ gram} \end{cases}$
Proton rest energy	$m_p c^2 = 1.503279 \times \begin{cases} 10^{-10} \text{ joules} \\ 10^{-3} \text{ ergs} \end{cases}$ $= 938.272 \text{ MeV}$
Mass of Earth	$M_{\oplus} = 5.9742 \times \begin{cases} 10^{24} \text{ kilograms} \\ 10^{27} \text{ grams} \end{cases}$
Radius of a sphere having the same volume as Earth	$R_{\oplus} = 6.3710 \times \begin{cases} 10^6 \text{ meters} \\ 10^8 \text{ centimeters} \end{cases}$
Mean distance of Earth from Sun = "astronomical unit"	$AU = 1.495978 \times \begin{cases} 10^{11} \text{ meters} \\ 10^{13} \text{ centimeters} \end{cases}$
Mean speed of Earth in its orbit about Sun	$v = 29.78 \text{ kilometers/second}$
Mean distance of Moon from Earth	$3.844 \times \begin{cases} 10^8 \text{ meters} \\ 10^{10} \text{ centimeters} \end{cases}$
Mass of Sun	$M_{\odot} = 1.989 \times \begin{cases} 10^{30} \text{ kilograms} \\ 10^{33} \text{ grams} \end{cases}$
Mean radius of Sun	$R_{\odot} = 6.9599 \times \begin{cases} 10^8 \text{ meters} \\ 10^{10} \text{ centimeters} \end{cases}$

Conversion Factors

1 second = $2.99792458 \times \begin{cases} 10^8 \text{ meters} \\ 10^{10} \text{ centimeters} \end{cases}$	of light-travel time
1 meter of light-travel time = 3.335641×10^{-9}	second
1 centimeter of light-travel time = 3.335641×10^{-11}	second
1 year = 3.156×10^7 seconds = $9.460 \times \begin{cases} 10^{15} \text{ meters} \\ 10^{17} \text{ centimeters} \end{cases}$	of light-travel time
1 kilometer = 0.6214	mile
1 electron-volt = 1.602×10^{-19}	joule = 1.602×10^{-12} erg

THE AUTHORS

JOHN ARCHIBALD WHEELER (Ph.D., Johns Hopkins University) is one of the world's foremost relativists. He is Joseph Henry Professor Emeritus at Princeton University and, until his retirement in 1986, Blumberg Professor of Physics and Director, Center for Theoretical Physics, at the University of Texas at Austin. A past president of the American Physical Society, he is a recipient of the Enrico Fermi Award (1968), the National Medal of Science (1971), and the Niels Bohr International Gold Medal (1982).

Since the appearance of the First Edition of *Spacetime Physics*, John Wheeler has published a graduate text in general relativity, *GRAVITATION*, with Kip S. Thorne and Charles W. Misner (W. H. Freeman, 1970), and a popular treatment of gravity, *A Journey into Gravity and Spacetime* (Scientific American Library, 1990; distributed by W. H. Freeman).

EDWIN F. TAYLOR (Ph.D., Harvard University) taught physics for 26 years at the Massachusetts Institute of Technology. He is currently Research Professor in the Department of Physics at Boston University. He is the author of a textbook on introductory mechanics and *An Introduction to Quantum Physics* with A. P. French (W. W. Norton, 1978). He has served as Editor of the *American Journal of Physics*.

With MIT undergraduates, Edwin Taylor produced interactive computer programs to help students visualize and solve problems in special relativity. These won the 1988 EDUCOM/NCRIPTAL Higher Education Software Awards for Best Physics Software and Best Tool Software.

THE BOOK

Collaboration on the First Edition of *Spacetime Physics* began in the mid-1960s when Edwin Taylor took a junior faculty sabbatical at Princeton University where John Wheeler was a professor. The resulting text emphasized the unity of spacetime and those quantities (such as proper time, proper distance, mass) that are invariant, the same for all observers, rather than those quantities (such as space and time separations) that are relative, different for different observers. The text has become a standard for modern physics and relativity courses, as well as introductory physics.

The Second Edition of *Spacetime Physics* embodies what the authors have learned during an additional quarter century of teaching and research. They have updated the text to reflect the immense strides in physics during the same period and modernized and increased the number of exercises, for which the First Edition was famous. Enrichment boxes provide expanded coverage of intriguing topics. Sample problems encourage students to exercise their newfound power. An enlarged final chapter on general relativity includes new material on gravity waves, black holes, and cosmology.

The Second Edition of *Spacetime Physics* provides a new generation of students with a deep and simple overview of the principles of relativity.



W. H. Freeman and Company
41 Madison Avenue New York, NY 10010
20 Beaumont Street Oxford OX1 2NQ

ISBN-13: 978-0-7167-2327-1

ISBN-10: 0-7167-2327-1

EAN
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