

Contents

1 Kinematics, Part 1	1
1.1 Motivation	2
1.1.1 Galilean transformations, Maxwell's equations	2
1.1.2 Michelson–Morley experiment	5
1.2 The postulates	10
1.3 The fundamental effects	12
1.3.1 Loss of simultaneity	12
1.3.2 Time dilation	17
1.3.3 Length contraction	23
1.3.4 A few other important topics	28
1.4 Four instructive examples	31
1.5 Velocity addition	35
1.6 Summary	43
1.7 Problems	44
1.8 Exercises	49
1.9 Solutions	54
2 Kinematics, Part 2	71
2.1 Lorentz transformations	71
2.1.1 First derivation	72
2.1.2 Second derivation	75
2.1.3 The fundamental effects	78
2.2 Velocity addition	79
2.2.1 Longitudinal velocity addition	79
2.2.2 Transverse velocity addition	80
2.3 The invariant interval	82
2.4 Minkowski diagrams	87
2.5 The Doppler effect	92
2.5.1 Longitudinal Doppler effect	92
2.5.2 Transverse Doppler effect	94
2.6 Rapidity	96
2.6.1 Definition	96
2.6.2 Physical meaning	98
2.7 Relativity without c	99
2.8 Summary	102
2.9 Problems	103
2.10 Exercises	106
2.11 Solutions	110

3	Dynamics	123
3.1	Energy and momentum	123
3.1.1	Momentum	124
3.1.2	Energy	125
3.2	Transformations of E and p	131
3.3	Collisions and decays	134
3.4	Particle-physics units	139
3.5	Force	140
3.5.1	Force in one dimension	140
3.5.2	Force in two dimensions	142
3.5.3	Transformation of forces	143
3.6	Rocket motion	145
3.7	Relativistic strings	149
3.8	Summary	150
3.9	Problems	151
3.10	Exercises	155
3.11	Solutions	159
4	4-vectors	177
4.1	Definition of 4-vectors	177
4.2	Examples of 4-vectors	178
4.3	Properties of 4-vectors	181
4.4	Energy, momentum	183
4.4.1	Norm	183
4.4.2	Transformations of E and p	183
4.5	Force and acceleration	184
4.5.1	Transformation of forces	184
4.5.2	Transformation of accelerations	185
4.6	The form of physical laws	186
4.7	Summary	187
4.8	Problems	188
4.9	Exercises	188
4.10	Solutions	189
5	General Relativity	192
5.1	The Equivalence Principle	192
5.2	Time dilation	194
5.3	Uniformly accelerating frame	197
5.3.1	Uniformly accelerating point particle	197
5.3.2	Uniformly accelerating frame	199
5.4	Maximal-proper-time principle	200
5.5	Twin paradox revisited	202
5.6	Summary	204
5.7	Problems	204
5.8	Exercises	208
5.9	Solutions	211

6	Appendices	225
6.1	Appendix A: Qualitative relativity questions	225
6.2	Appendix B: Derivations of the Lv/c^2 result	235
6.3	Appendix C: Resolutions to the twin paradox	237
6.4	Appendix D: Lorentz transformations	238
6.5	Appendix E: Nonrelativistic dynamics	241
6.6	Appendix F: Problem-solving strategies	245
6.6.1	Solving problems symbolically	245
6.6.2	Checking units/dimensions	246
6.6.3	Checking limiting/special cases	248
6.6.4	Taylor series	249
6.7	Appendix G: Taylor series	251
6.7.1	Basics	251
6.7.2	How many terms to keep?	253
6.7.3	Dimensionless quantities	254
6.8	Appendix H: Useful formulas	255
6.9	References	256

This book is a revised and expanded version of the last four chapters in my textbook *Introduction to Classical Mechanics, with Problems and Solutions* (Cambridge University Press, 2008). A great deal of additional commentary has been included in order to make the book accessible to a wider audience. This new version assumes a high familiarity with standard Newtonian physics (often called “ freshman physics ”). More precisely, the first two chapters (on kinematics) assume very little prior physics knowledge; there is no mention of force, energy, momentum, etc. But Chapter 3 and onward assume a bit more, although still not a huge amount. (Appendix E gives a quick review of force, etc., for readers with a limited physics background.) The one thing for not-to-over-thing, depending on your point of view) about relativity is that it is challenging due to its inherent strangeness, as opposed to a heavy set of physics prerequisites. Likewise for the math prerequisite: calculus is used on a few occasions, but it isn’t essential to the overall flow of the book. Generally, all that is required is standard algebra.

If you happen to have a strong background in standard Newtonian physics, then you might be in for a shock, because relativity is where you discover that most of what you know about physics is wrong. Or perhaps “ incomplete ” would be a better word. The important point to realize is that Newtonian physics is a limiting case of the more correct relativistic theory. Newtonian physics works perfectly fine when the speeds you’re dealing with are much less than the speed of light. Indeed, it would be silly to use relativity to solve a problem involving the length of a baseball trajectory. But in problems involving large speeds, or in problems where a high degree of accuracy is required, you must use the relativistic theory.

Of course, relativity isn’t the end of the story either. In your future physics studies, you will eventually discover that classical special relativity (the subject of this book) is simply the limiting case of another theory (quantum field theory). And likewise, quantum field theory is the limiting case of yet another theory (string theory). And likewise . . . well, you get the idea. Who knows, maybe it really *is* turtles all the way down.

There are two main topics in relativity: special relativity (which doesn’t deal with gravity) and general relativity (which does). We’ll deal mostly with the former, although Chapter 5 contains a brief introduction to the latter. Special relativity may be divided into two topics, kinematics and dynamics. Kinematics deals with lengths, times, speeds, etc. It is concerned only with the space and time coordinates of an abstract particle,