

# General Relativity: Exercises 2 -Solutions

May 25, 2011

## Homework 1: Foucault Pendulum

Equations of parallel transport of vector  $V$  are

$$\dot{V}^\mu + \Gamma_{\alpha\beta}^\mu V^\alpha \dot{x}^\beta = 0, \quad (1)$$

where dot means differentiation according to  $t$ . Taking Christoffel symbols for 2-spheres and choosing parametrization  $t = \phi$  we obtain system of coupled differential equations

$$\dot{V}^\theta - \sin \theta_0 \cos \theta_0 \dot{\phi} V^\phi = 0, \quad (2)$$

$$\dot{V}^\phi + \cot \theta_0 V^\theta = 0. \quad (3)$$

We can solve this system by differentiating first equation according to  $\phi$  and inserting second equation into it. We obtain differential equation of second order

$$\ddot{V}^\theta + \cos^2 \theta_0 V^\theta = 0, \quad (4)$$

Solution to this differential equation is given by

$$V^\theta = A \cos(\phi \cos \theta_0) + B \sin(\phi \cos \theta_0), \quad (5)$$

where  $A$  and  $B$  are integration constants which we can determine from condition  $V = (V^\theta, V^\phi) = (0, 1)$  at  $\phi = 0$ . We obtain  $A = 1$  and  $B = 0$ . With knowledge of  $V^\theta$  we can find (3) to be

$$\dot{V}^\phi = -\cot \theta_0 V^\theta = -\cot \theta_0 \cos[\phi \cos \theta_0], \quad (6)$$

which can be easily integrated and thus we obtain final solution

$$V^\theta = \cos[\phi \cos \theta_0], \quad (7)$$

$$V^\phi = -\frac{\sin[\phi \cos \theta_0]}{\sin \theta_0}. \quad (8)$$

To find angle by which is vector rotated we need

$$\cos \alpha = \frac{V \cdot V'}{|V| |V'|} \quad (9)$$

where  $V$  is  $V = V(\phi = 0)$  and  $V'$  is after parallel transport, i.e.  $V' = V(\phi = 2\pi)$  From there we can see that after parallel transport around full circle, i.e. from  $\phi = 0$  to  $\phi = 2\pi$ , vector  $V$  will be rotated by angle

$$\alpha = 2\pi \cos \theta_0, \quad (10)$$

what is exactly angle by which Foucault pendulum will be rotated by one day. This is because motion of Foucault pendulum is inertial, i.e. is parallelly transported. In one day it is parallelly transported around full circle (because of rotation of Earth surface).

# General Relativity Solutions To Exercises

**Robert W. Batterman**



## **General Relativity Solutions To Exercises:**

**Solutions of Exercises of General Relativity Simplified & Assessed** Taha Sochi, This book contains detailed solutions of all the 606 exercises of my book General Relativity Simplified Assessed These exercises represent an integral part of the original book as they fill many gaps and provide essential extensions and elaborations

**Introduction To General Relativity And Cosmology** Christian G Boehmer, 2016-10-06 Introduction to General Relativity and Cosmology gives undergraduate students an overview of the fundamental ideas behind the geometric theory of gravitation and spacetime Through pointers on how to modify and generalise Einstein's theory to enhance understanding it provides a link between standard textbook content and current research in the field Chapters present complicated material practically and concisely initially dealing with the mathematical foundations of the theory of relativity in particular differential geometry This is followed by a discussion of the Einstein field equations and their various properties Also given is analysis of the important Schwarzschild solutions followed by application of general relativity to cosmology Questions with fully worked answers are provided at the end of each chapter to aid comprehension and guide learning This pared down textbook is specifically designed for new students looking for a workable simple presentation of some of the key theories in modern physics and mathematics

General Relativity Without Calculus Jose Natario, 2011-07-30 General Relativity Without Calculus offers a compact but mathematically correct introduction to the general theory of relativity assuming only a basic knowledge of high school mathematics and physics Targeted at first year undergraduates and advanced high school students who wish to learn Einstein's theory beyond popular science accounts it covers the basics of special relativity Minkowski space time non Euclidean geometry Newtonian gravity the Schwarzschild solution black holes and cosmology The quick paced style is balanced by over 75 exercises including full solutions allowing readers to test and consolidate their understanding

**Student Solutions Manual for Mathematical Methods for Physics and Engineering** Kenneth Franklin Riley, Michael Paul Hobson, 2006 The authors present a wide ranging and comprehensive textbook for physical scientists who need to use the tools of mathematics for practical purposes

*Mathematical Introduction To General Relativity, A (Second Edition)* Amol Sasane, 2024-12-20 The book aims to give a mathematical presentation of the theory of general relativity that is spacetime geometry based gravitation theory to advanced undergraduate mathematics students Mathematicians will find spacetime physics presented in the definition theorem proof format familiar to them The given precise mathematical definitions of physical notions help avoiding pitfalls especially in the context of spacetime physics describing phenomena that are counter intuitive to everyday experiences In the first part the differential geometry of smooth manifolds which is needed to present the spacetime based gravitation theory is developed from scratch Here many of the illustrating examples are the Lorentzian manifolds which later serve as spacetime models This has the twofold purpose of making the physics forthcoming in the second part relatable and the mathematics learnt in the first part less dry The book uses the modern coordinate free

language of semi Riemannian geometry Nevertheless to familiarise the reader with the useful tool of coordinates for computations and to bridge the gap with the physics literature the link to coordinates is made through exercises and via frequent remarks on how the two languages are related In the second part the focus is on physics covering essential material of the 20th century spacetime based view of gravity energy momentum tensor field of matter field equation spacetime examples Newtonian approximation geodesics tests of the theory black holes and cosmological models of the universe Prior knowledge of differential geometry or physics is not assumed The book is intended for self study and the solutions to all the 283 exercises are included The second edition corrects errors from the first edition and includes 60 new exercises 10 new remarks 29 new figures some of which cover auxiliary topics that were omitted in the first edition

### **Pseudo-Complex**

**General Relativity** Peter O. Hess, Mirko Schäfer, Walter Greiner, 2015-10-31 This book explores the role of singularities in general relativity GR The theory predicts that when a sufficient large mass collapses no known force is able to stop it until all mass is concentrated at a point The question arises whether an acceptable physical theory should have a singularity not even a coordinate singularity The appearance of a singularity shows the limitations of the theory In GR this limitation is the strong gravitational force acting near and at a super massive concentration of a central mass First a historical overview is given on former attempts to extend GR which includes Einstein himself all with distinct motivations It will be shown that the only possible algebraic extension is to introduce pseudo complex pc coordinates otherwise for weak gravitational fields non physical ghost solutions appear Thus the need to use pc variables We will see that the theory contains a minimal length with important consequences After that the pc GR is formulated and compared to the former attempts A new variational principle is introduced which requires in the Einstein equations an additional contribution Alternatively the standard variational principle can be applied but one has to introduce a constraint with the same former results The additional contribution will be associated to vacuum fluctuation whose dependence on the radial distance can be approximately obtained using semi classical Quantum Mechanics The main point is that pc GR predicts that mass not only curves the space but also changes the vacuum structure of the space itself In the following chapters the minimal length will be set to zero due to its smallness Nevertheless the pc GR will keep a remnant of the pc description namely that the appearance of a term which we may call dark energy is inevitable The first application will be discussed in chapter 3 namely solutions of central mass distributions For a non rotating massive object it is the pc Schwarzschild solution for a rotating massive object the pc Kerr solution and for a charged massive object it will be the Reissner Nordström solution This chapter serves to become familiar on how to resolve problems in pc GR and on how to interpret the results One of the main consequences is that we can eliminate the event horizon and thus there will be no black holes The huge massive objects in the center of nearly any galaxy and the so called galactic black holes are within pc GR still there but with the absence of an event horizon Chapter 4 gives another application of the theory namely the Robertson Walker solution which we use to model different outcomes of the evolution of the

universe Finally the capability of this theory to predict new phenomena is illustrated

**General Relativity Simplified & Assessed** Taha Sochi, 2022-08-17 This book is about the general theory of relativity which is concisely labeled as general relativity The book is the result of a rather extensive view to the literature of this theory over most of its lifetime reflecting various stages of its development The book contains 129 solved problems as well as 606 exercises whose detailed solutions are published in another book that accompanies the present book The book also includes a detailed index and many cross references The book can be used as an introduction to general relativity at undergraduate and graduate levels Unlike most other books on general relativity which are mostly dedicated to the presentation justification application and validation of the formalism of the theory and hence rather minor attention is usually paid to the interpretation and epistemology of the theory this book is primarily interested in the interpretative and epistemological aspects of the theory

*A Student's Manual for A First Course in General Relativity* Robert B. Scott, 2016-01-21 This comprehensive student manual has been designed to accompany the leading textbook by Bernard Schutz *A First Course in General Relativity* and uses detailed solutions cross referenced to several introductory and more advanced textbooks to enable self learners undergraduates and postgraduates to master general relativity through problem solving The perfect accompaniment to Schutz's textbook this manual guides the reader step by step through over 200 exercises with clear easy to follow derivations It provides detailed solutions to almost half of Schutz's exercises and includes 125 brand new supplementary problems that address the subtle points of each chapter It includes a comprehensive index and collects useful mathematical results such as transformation matrices and Christoffel symbols for commonly studied spacetimes in an appendix Supported by an online table categorising exercises a Maple worksheet and an instructors manual this text provides an invaluable resource for all students and instructors using Schutz's textbook

*Lectures on General Relativity* A. Papapetrou, 1974-11-30 This book is an elaboration of lecture notes for the graduate course on General Relativity given by the author at Boston University in the spring semester of 1972 It is an introduction to the subject only as the time available for the course was limited The author of an introduction to General Relativity is faced from the beginning with the difficult task of choosing which material to include A general criterion assisting in this choice is provided by the didactic character of the book Those chapters have to be included in priority which will be most useful to the reader in enabling him to understand the methods used in General Relativity the results obtained so far and possibly the problems still to be solved This criterion is not sufficient to ensure a unique choice General Relativity has developed to such a degree that it is impossible to include in an introductory textbook of a reasonable length even a very condensed treatment of all important problems which have been discussed until now and the author is obliged to decide in a more or less subjective manner which of the more recent developments to omit The following lines indicate by means of some examples the kind of choice made in this book

**String Theory Methods for Condensed Matter Physics** Horatiu Nastase, 2017-09-21 The discovery of a duality between Anti de Sitter spaces AdS and Conformal Field Theories CFT has led

to major advances in our understanding of quantum field theory and quantum gravity String theory methods and AdS CFT correspondence maps provide new ways to think about difficult condensed matter problems String theory methods based on the AdS CFT correspondence allow us to transform problems so they have weak interactions and can be solved more easily They can also help map problems to different descriptions for instance mapping the description of a fluid using the Navier Stokes equations to the description of an event horizon of a black hole using Einstein's equations This textbook covers the applications of string theory methods and the mathematics of AdS CFT to areas of condensed matter physics Bridging the gap between string theory and condensed matter this is a valuable textbook for students and researchers in both fields

Classical Field Theory Horațiu Năstase, 2019-03-14 An introduction to classical field theory focusing on methods and solutions providing a foundation for the study of quantum field theory

**Cosmology** Nicola Vittorio, 2017-11-15 Modern cosmology has changed significantly over the years from the discovery to the precision measurement era The data now available provide a wealth of information mostly consistent with a model where dark matter and dark energy are in a rough proportion of 3 : 7 The time is right for a fresh new textbook which captures the state of the art in cosmology Written by one of the world's leading cosmologists this brand new thoroughly class tested textbook provides graduate and undergraduate students with coverage of the very latest developments and experimental results in the field Prof Nicola Vittorio shows what is meant by precision cosmology from both theoretical and observational perspectives This book is divided into three main parts Part I provides a pedagogical but rigorous general relativity based discussion of cosmological models showing the evidence for dark energy the constraints from primordial nucleosynthesis and the need for inflation Part II introduces density fluctuations and their statistical description discussing different theoretical scenarios such as  $\Lambda$ CDM as well as observations Part III introduces the general relativity approach to structure formation and discusses the physics behind the CMB temperature and polarization pattern of the microwave sky Carefully adapted from the course taught by Prof Vittorio at the University of Rome Tor Vergata this book will be an ideal companion for advanced students undertaking a course in cosmology Features Incorporates the latest experimental results at a time of rapid change in this field with balanced coverage of both theoretical and experimental perspectives Each chapter is accompanied by problems with detailed solutions The basics of tensor calculus and GR are given in the appendices

**General Relativity** Norbert Straumann, 2012-10-08 This book provides a completely revised and expanded version of the previous classic edition General Relativity and Relativistic Astrophysics In Part I the foundations of general relativity are thoroughly developed while Part II is devoted to tests of general relativity and many of its applications Binary pulsars our best laboratories for general relativity are studied in considerable detail An introduction to gravitational lensing theory is included as well so as to make the current literature on the subject accessible to readers Considerable attention is devoted to the study of compact objects especially to black holes This includes a detailed derivation of the Kerr solution Israel's proof of his uniqueness theorem and a derivation of the basic

laws of black hole physics Part II ends with Witten's proof of the positive energy theorem which is presented in detail together with the required tools on spin structures and spinor analysis In Part III all of the differential geometric tools required are developed in detail A great deal of effort went into refining and improving the text for the new edition New material has been added including a chapter on cosmology The book addresses undergraduate and graduate students in physics astrophysics and mathematics It utilizes a very well structured approach which should help it continue to be a standard work for a modern treatment of gravitational physics The clear presentation of differential geometry also makes it useful for work on string theory and other fields of physics classical as well as quantum **Gravitation** Charles W.

Misner, Kip S. Thorne, John Archibald Wheeler, 2017-10-24 Spacetime physics Physics in flat spacetime The mathematics of curved spacetime Einstein's geometric theory of gravity Relativistic stars The universe Gravitational collapse and black holes Gravitational waves Experimental tests of general relativity Frontiers **An Introduction to General Relativity and**

**Cosmology** Jerzy Plebanski, Andrzej Krasinski, 2006-08-14 General relativity is a cornerstone of modern physics and is of major importance in its applications to cosmology Plebanski and Krasinski are experts in the field and in this book they provide a thorough introduction to general relativity guiding the reader through complete derivations of the most important results Providing coverage from a unique viewpoint geometrical physical and astrophysical properties of inhomogeneous cosmological models are all systematically and clearly presented allowing the reader to follow and verify all derivations For advanced undergraduates and graduates in physics and astronomy this textbook will enable students to develop expertise in the mathematical techniques necessary to study general relativity *Introduction to AdS/CFT Correspondence* Horațiu Năstase, 2015-09-10 A pedagogical and self contained introduction to AdS/CFT correspondence aimed at graduate students and researchers across theoretical physics **Matrix-geometric Solutions in Stochastic Models** Marcel F.

Neuts, 1994-01-01 Topics include matrix geometric invariant vectors buffer models queues in a random environment and more **Elementary General Relativity** C. Clarke, Christopher James Seaton Clarke, 1980 Spacetime, Geometry and

Gravitation Pankaj Sharan, 2009-11-18 This is an introductory book on the general theory of relativity based partly on lectures given to students of M Sc Physics at my university The book is divided into three parts The first part is a preliminary course on general relativity with minimum preparation The second part builds the mathematical background and the third part deals with topics where mathematics developed in the second part is needed The first chapter gives a general background and introduction This is followed by an introduction to curvature through Gauss Theorema Egregium This theorem expresses the curvature of a two dimensional surface in terms of intrinsic quantities related to the infinitesimal distance function on the surface The student is introduced to the metric tensor Christoffel symbols and Riemann curvature tensor by elementary methods in the familiar and visualizable case of two dimensions This early introduction to geometric quantities equips a student to learn simpler topics in general relativity like the Newtonian limit red shift the Schwarzschild solution precession of the perihelion

and bending of light in a gravitational field Part II chapters 5 to 10 is an introduction to Riemannian geometry as required by general relativity This is done from the beginning starting with vectors and tensors I believe that students of physics grasp physical concepts better if they are not shaky about the mathematics involved

**The Oxford Handbook of Philosophy of Physics** Robert W. Batterman, 2013-01-04 This Oxford Handbook provides an overview of many of the topics that currently engage philosophers of physics It surveys new issues and the problems that have become a focus of attention in recent years It also provides up to date discussions of the still very important problems that dominated the field in the past In the late 20th Century the philosophy of physics was largely focused on orthodox Quantum Mechanics and Relativity Theory The measurement problem the question of the possibility of hidden variables and the nature of quantum locality dominated the literature on the quantum mechanics whereas questions about relationalism vs substantivalism and issues about underdetermination of theories dominated the literature on spacetime These issues still receive considerable attention from philosophers but many have shifted their attentions to other questions related to quantum mechanics and to spacetime theories Quantum field theory has become a major focus particularly from the point of view of algebraic foundations Concurrent with these trends there has been a focus on understanding gauge invariance and symmetries The philosophy of physics has evolved even further in recent years with attention being paid to theories that for the most part were largely ignored in the past For example the relationship between thermodynamics and statistical mechanics once thought to be a paradigm instance of unproblematic theory reduction is now a hotly debated topic The implicit and sometimes explicit reductionist methodology of both philosophers and physicists has been severely criticized and attention has now turned to the explanatory and descriptive roles of non fundamental phenomenological theories This shift of attention includes old theories such as classical mechanics once deemed to be of little philosophical interest Furthermore some philosophers have become more interested in less fundamental contemporary physics such as condensed matter theory Questions abound with implications for the nature of models idealizations and explanation in physics This Handbook showcases all these aspects of this complex and dynamic discipline

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