Einstein's General Theory of Relativity and Gravitation

(Physics 255)

Professor Herbert W. Hamber

The graduate General Relativity course is taught by Professor Herbert W. Hamber, Ph.D.

References used for the class include "Gravitation and Cosmology" by S. Weinberg,
"Gravity: An Introduction to Einstein's General Relativity" by J. Hartle,
"Lectures on Gravitation" by R.P. Feynman and "Quantum Gravitation" by H.W. Hamber.

Lecture 1. Recorded April 1, 2014.

"A Brief History of Gravity"

Gravity from the Ancient Greeks to Einstein's Relativistic Theory (1907)

Lecture 2. Recorded April 3, 2014.

"Special Relativity 1."

Lorentz Transformations. Euclidean vs. Lorentzian Signature. Proper time. Flat metric. Time dilation. Energy and Momentum. Four-force and Relativistic Equations of Motion.

Lecture 3. Recorded April 8, 2014.

"Special Relativity 2."

Four-vectors and Tensors. Covariant and Contravariant Forms. Tensor algebra. Covariant form of Maxwell's Equations. Conservation Laws. Energy-Momentum Tensor.

Lecture 4. Recorded April 10, 2014.

"Special Relativity 3."

Angular Momentum and Spin. Conservation Laws. Relativistic Hydrodynamics. Perfect Fluid. Possible Equations of State. Irreducible Representations of the Lorentz Group. Allowed Values for the Quantum Spin.

Lecture 5. Recorded April 15, 2014.

"General Relativity 1."

Non-Relativistic (Newtonian) Gravity. Freely Falling Observers.
Principle of Equivalence. Statement of the Principle. Supporting Measurements (Eötvös Experiment). Equation of
Free Fall (Geodesic Equation). Metric Tensor and Affine Connection.

Lecture 6. Recorded April 17, 2014.

"General Relativity 2."

Proper Time and the Derivation of the Equation of Free Fall
from a Variational Principle. Significance for the Quantum Mechanical Feynman Path Integral. Newtonian Limit. Time
Dilation and Gravitational Red Shift. Order of Magnitude Estimates.

Lecture 7. Recorded April 22, 2014.

"General Relativity 3."

Precision Test of the Equivalence Principle. GR Time Dilation
Effects in GPS Systems. Searches for a Possible Anisotropy of Inertia. Equation of Free Fall compared to Newton's Equation. Electromagnetic Analogy (Lorentz Force). The Scale of Time and the Magnitude of the Metric. Asymptotically Flat Metrics as Idealizations. Role of Mach's Principle and the Origin of G. Simple Examples of Coordinate Systems. Coordinate Dependence of the Affine Connection.

Lecture 8. Recorded April 24, 2014.

“General Relativity 4.”

Principle of General Covariance. Local versus Global Invariances. Gauge Fields and the QED Analogy. General
Structure of Invariant Equations. Tensor Algebra, Raising and Lowering of Indices, Contractions. Tensor Densities, Space-Time Volume Element. Transformation Properties of the Affine Connection. General Coordinate Invariance of the Equation of Free Fall.

Lecture 9. Recorded April 29, 2014.

“General Relativity 5.

Covariant Derivative. Covariant Derivative of the Metric.
Covariant Differentiation along a Path. Examples of Parallel
Transports for a Vector. Covariant Curls and Divergences.
Finite Parallel Transports with Path Ordered Products.
Gauge Invariance and Covariant Derivative in QED.

Lecture 10. Recorded May 1, 2014.

“General Relativity 6.”

Particle Mechanics in the Presence of Gravity. Fermi-Walker Transport. Electrodynamics in Covariant Form. Conserved Energy-Momentum Tensor. Hydrodynamic Equations for a Perfect Fluid. Riemann Curvature Tensor. Parallel Transport Around an Infinitesimal Closed Loop. Gravitation versus Curvilinear Coordinates. Algebraic Properties of the Riemann Tensor. Differential (Bianchi) Identities.

Lecture 11. Recorded May 6, 2014.

“Field Equations 1.”

Derivation of the Einstein Field Equations. Requirement of General Covariance, Nonrelativistic Limit. Equivalent Forms for the Field Equations. Vacuum Solutions. Cosmological Constant Term. Modifications to Newtonian Gravity. Cosmological Constant
as Gravitational Vacuum Energy.

Lecture 12. Recorded May 8, 2014.

"Field Equations 2."

Einstein-Hilbert Action, Variational Principle, Palatini Identity. Role of the Action in Constructing the Feynman Path Integral for Quantized Gravity. Gravitational Functional Measure. Need to Maintain General Covariance. Scalar-Tensor Extensions of Gravity. Brans-Dicke Theory. Field Equation Modifications from the Massless BD Scalar.

Lecture 13. Recorded May 13, 2014.

"Field Equations 3."

Field Degrees of Freedom and Constraints. Coordinate Conditions. Analogy to Gauge Choice in Electrodynamics. Physical Degrees of Freedom. Harmonic Gauge. Weak Field Expansion, Linear Part of the Ricci Tensor. Asymptotically Flat Metrics. Energy, Momentum and Angular Momentum of a Gravitational Field. Static Isotropic Metric. Derivation of the Solution to the Field Equations for the Static Isotropic Metric.

Lecture 14. Recorded May 15, 2014.

"Solutions to the Field Equations 1."

Schwarzschild Solution. Gravitational Redshift near the Horizon. Coordinate Dependence of Horizon. Kruskal Coordinates. Stationary versus Freely Falling Observers. Kruskal Diagram. The Metric Inside a Star. Astrophysical Black Holes. Equations of Motion for a Particle in the Schwarzschild Metric. Integrals of the Motion. Radial Equation and Effective Potential.

Lecture 15. Recorded May 20, 2014.

"Solutions to the Field Equations 2."

Equations for Orbits. Relativistic Correction to the Newtonian Potential. Precession of the Perihelion of Mercury. Celestial

Reference Frames. Photon Orbits in the Schwarzschild Metric. Deflection of Light by the Sun. Radar Echo Delay. Robertson Expansion. Present Status of Solar System Tests of General Relativity.

Lecture 16. Recorded May 22, 2014.

“Solutions to the Field Equations 3.”

Weak and Strong Gravitational Fields. The Weak Field Expansion. Choice of Background Metric. Linear Part of the Ricci Tensor. Local Gauge Invariance. Gauge Conditions. Wave Equation and Explicit Solution in Terms of Retarded Potentials. Plane Wave Solutions. Polarization Amplitudes. Transverse Traceless Modes as Physical Modes. Spin Two of the Graviton.

Lecture 17. Recorded May 27, 2014.

“Solutions to the Field Equations 4.”

Polarization States for a Gravitational Wave. Generation of Gravitational Waves. Far Field Limit. Expansion in Fourier Components. Angular Dependence of Power Radiated. Quadrupole Radiation. Total Power Emitted. Gravitational Waves Emitted by a Rotating Body. Detection of Gravitational Waves. Bar Detectors and Large Interferometer Detectors.

Lecture 18. Recorded May 29, 2014.

“Solutions to the Field Equations 5.”

Lense-Thirring Effect and Mach's Principle. Solution of the Field Equations for a Thin Rotating Spherical Shell. Strong Field Case as Obtained from the Kerr Solution. Newton's Constant and Mass Distribution in the Universe. Field Equations Relevant for Cosmology. Assumption of Homogeneity and Isotropy for the Universe. Friedman-Robertson-Walker Metric. Structure of the Field Equations for a Perfect Fluid.

Lecture 19. Recorded June 3, 2014.

"Solutions to the Field Equations 6."

Solutions to the Field Equations for a Homogeneous Isotropic Metric. Relation to Newtonian Mechanics. Matter Dominated Universe. Effects of Radiation and of the Cosmological Constant. Density and Pressure of the Present Universe. Evolution of the Black Body Temperature. Estimates for the Hubble Constant. Relative Contributions of Vacuum Energy and Matter in the Present Universe.

Lecture 20. Recorded June 5, 2014.

"Gravitation and Quantum Mechanics"

Gravitational Field as a Collection of Gravitons. Quantum-Mechanical Field Fluctuations. The Path Integral Approach to Gravity and the Need to Retain General Covariance. DeWitt's Functional Measure over Metrics. Feynman's Derivation of the Field Equations for Gravity from the Construction of a Lagrangian for a Massless Spin-Two Particle. Nonlinear Terms due to the Graviton's own Energy and Momentum. Short Distance Modifications to Gravity due to Radiative Corrections.

GR Class Student Presentations - Group 1

Benjamin Boizelle	Kerr Solution for a Rotating Black Hole
Anna Kwa	Gravitational Lensing
Christopher Persichilli	Gravitational Wave Generation and Detection
Nicolas Canac	Frame Dragging for Satellites

GR Class Student Presentations - Group 2

Yucheng Ji	Positive Energy Theorem in GR
James Asbrock	Curvature in D=2,3,4 and Higher Dimensions
Andrew Yang	Two-Dimensional Gravity

GR Class Student Presentations - Group 3

Andrew Pace	MOND (Modified Newtonian Mechanics) and GR
Craig Pitcher	Dark Matter Candidates (Neutrinos, Machos, Wimps etc.)
Anthony DiFranzo	Hierarchy Problem and the Planck Mass
Mohammad Abdullah	Cosmological Inflation

GR Class Student Presentations - Group 4

Meghan Frate	Higher Dimensional Gravity (Kaluza-Klein Theory)
Jennifer Rittenhouse West	Curvature Squared ($R + R^2$) Gravity
Aaron Soffa	Tetrad (Vierbein) Formalism and the Dirac Equation
Michael Gordon	Feynman Rules and Diagrams for Quantum Gravity