- **PH236 GENERAL RELATIVITY 2007-2008**
- ***Topics Actually Covered First Term;***
- ***Tentative Plans for Second & Third Terms***
- *[by Kip, 9 December 2007]*
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- ***First Term:*** Taught by *Kip Thorne*

Week 1
- **A Overview and Motivations**
  - 1 The Basic Concepts of General Relativity
  - 2 The Warped Side of the Universe
  - 3 Impending Revolution Triggered By Numerical Relativity and Gravitational Wave Observations
- **B Special Relativity (physics in flat spacetime)**

Week 1
  - 1 ***Fundamental Concepts of Special Relativity***
    - a Lorentz frames, principle of relativity, events, invariant interval, Lorentz boosts, measuring the interval

Weeks 1&2
  - 2 ***Differential Geometry in Flat Spacetime - in frame-invariant form***
    - a Events, curves, tangent vectors, inner product based on interval, tensors, metric tensor, directional derivative, gradient, tensor product, contraction

Week 2
  - 3 ***Laws of physics in frame-invariant form***
    - a **Principle of relativity:** Laws of physics expressed in frame-invariant, geometric form
    - b Applications: 4-momentum conservation; Lorentz force law
  - ***4 Differential Geometry: coordinate systems, bases and components***
    - a Slot-naming index notation
    - b Levi-Civita tensor
  - ***5 Laws of physics in component form***
    - a Particle kinetics, Lorentz Force Law
    - b Spacetime diagrams
    - c Paradoxes

Week 3
  - ***6 Volume Elements, Integration, Conservation Laws***
    - a Charge conservation, particle conservation
    - b Stress-energy tensor and 4-momentum conservation
  - ***7 Uniformly Accelerated Observers in Flat Spacetime***
    - a Gravitational redshift
- **C Foundations of General Relativity**
  - ***1 Differential Geometry in Curved Spacetime***
    - a Coordinate and non-coordinate bases
    - b Commutation coefficients
    - c Connection coefficients

- ***2 Geodesic Equation, Local Lorentz Frames***

Week 4

- 3 ***Tidal Gravity, Geodesic Deviation, and Spacetime Curvature***
  - a Newtonian tidal field
  - b Riemann curvature tensor and its roles in geodesic deviation, non-commutation of double gradients, parallel transport around closed curves
- ***4 Lifting the Laws of Physics Into Curved Spacetime***
  - a Curvature coupling: in Maxwell's equations, spin transport
- ***5 Einstein Field Equation***
  - a Derivation from Newton's source equation for gravity and the Principle of Relativity
  - b Cosmological Constant
  - c Prior Geometry and its role in reformulating the Principle of Relativity

Week 5

- ***6 General Relativistic Stars*** (as illustration of Einstein field equations)
  - a Static, spherical star
  - b Schwarzschild metric for star's exterior
  - c Slowly rotating star
- ***7 Local Lorentz Frames and Proper Reference Frames of Observers***
  - a mathematical construction of Local Lorentz frame; role of curvature at second order in distance from origin
  - b Proper reference frame of an accelerated, rotaing observer
- ***8 Symmetries of Spacetime and Conserved Quantities***
  - a Killing vector field and its use to construct conserved quantitites
- ***9 Physical Measurements in Curved Spacetime***
  - a Gravitational redshift as an example
- ***10 Conservation Laws for Total Mass, Momentum and Angular Momentum for an Isolated System***

Week 6

- **D Nonrotaing Black Holes and Wormholes**
  - 1 Schwarzschild Solution; Birkhoff's Theorem
  - 2 Implosion of a star to form a black hole
    - a Perturbations of collapse; stability of horizon; instability of singularity
    - b Cosmic censorship and naked singularities
  - 3 Nonrotating (Schwarzschild) wormhole
  - 4 Reissner-Nordstrom (charged) wormhole
  - 5 Static, spherical, traversable wormholes
  - 6 Time machine created from traversable wormhole
  - 7 Nonrotating (Schwarzschild) black hole: exterior, horizon and interior

Week 7

- **E Rotating Black Holes and Wormholes**
  - 1 Full Kerr spacetime geometry: multiple rotaing wormholes
  - 2 Black-hole formation via generic implosion: Kerr at late times in exterior and near horizon; not Kerr inside
  - 3 Kerr light cones, frame dragging, horizon generators, static limit, ergosphere, rotational energy extraction
  - 4 Laws of Black-Hole Mechanics
  - 5 Geodesics around rotating and nonrotating black holes

Week 8

- **F Weak Gravitational Fields**
  - 1 Linearized Theory
  - 2 Influence of gravity on matter: Post-Linear theory
  - 3 Newtonian Gravity
  - 4 Post-Newtonian gravity (just a few words)
- **G Gravitational Waves in Flat Spacetime**
  - 1 ***Linearized theory of gravitational wave propagation in flat spacetime***: TT field, Riemann tensor, geodesic deviation

Week 9

  - ***2 Wave generation by slow-motion sources.***
    - a Near zone, wave zone, slow-motion sources, multipolar expansion in brief
    - b Mass-quadrupole formalism: general outgoing-wave solution used to relate radiation field to Newtonian gravity of weak-field near zone
    - c Binary system as example
    - d Quadrupolar radiation reaction potential; energy loss from source
    - e General outgoing-wave solution for linearized theory, written as sum over multipole moments; its use to relate emitted waves to weak-field, near-zone, Newtonian Potential
  - ***3 Wave generation by black-hole binaries:***
    - a Overview of numerical relativity results
  - ***4 Gravitational wave detection***
    - a a few words (no more) about interferometers

Week 10

  - ***5 Gravitational waves propagating through curved spacetime***
    - a Two-lengthscale expansion
    - b GW stress-energy tensor: Its role in background Einstein equations; its conservation law
    - c Geometric optics: null rays, propagation of waves along rays, general outgoing-waves solution
    - d Comparison with EM waves: same redshifts, deflection of rays, gravitaitonal lensing
- **H General Relativity as a Nonlinear Field Theory in Flat Spacetime**
  - 1 Landau-Lifshitz formulation and equations

- 2 Application: Derivation of conservation laws for mass, momentum, and angular momentum of an isolated source

2nd Term

- ***Second Term: Ph236b & Ph237a -- Gravitational-Wave Sources and Phenomenology.*** Taught by *Yanbei Chen and Rana Adhikari*
  - **A Compact Binary Systems (Neutron Stars and Black holes) and the Gravitational Waves They Emit**
    - 1 Post-Newtonian Approximation and dynamics of binaries
    - 2 Phenomenology leading to stellar-mass compact-binary event rates for LIGO
    - 3 Dynamics and waveforms from extreme mass ratio inspirals (EMRIs) and Intermediate Mass Ratio Inspirals (IMRIs)
    - 4 Phenomenology of binaries involving supermassive black holes
  - **B Continuous Gravitational Waves and Pulsars**
    - 1 Pulsar phenomenology, including physical reasons for them to radiate GWs
  - **C Gravitational Wave (GW) Background Radiation**
    - 1 Inflation-amplified primordial background
    - 2 Phase transitions in early universe, cosmic strings, etc.
  - **D Burst Sources of Gravitational Waves**
    - 1 Supernovae explosions, gamma-ray bursts, new-born neutron stars
    - 2 GW bursts from cosmic-string cusps and kinks
  - **E Brief Overview of Numerical Relativity**
    - 1 Theory and formulation
    - 2 Simulations of gravitational-wave sources
  - **F Introduction to Theory of Random Processes, and Application to Noise in GW Detectors**

3rd Term of Ph237b

- ***Third Term: Ph237b -- Gravitational-Wave Detectors and Data Analysis.*** Taught by *Rana Adhikari and Yanbei Chen*
  - **A Ground-Based Interferometric Gravitational-Wave Detectors: LIGO and its Partners**
    - 1 Seismic noise and Newtonian gravity gradient noise
      - a Character of seismic noise, and seismic isolation systems
      - b Newtonian gravitational noise and ways to reduce it
    - 2 Thermal noise
      - a Fluctuation-dissipation theorem
      - b Theremal noise in test mass suspensions
      - c Thermal noise in mirrors and mirror coatings
    - 3 Quantum noise
    - 4 Laser noise

- a Laser amplitude noise: Sources and coupling mechanisms
- b Laser frequency noise: Couplings and limits on laser stabilization

- 5 Control systems
  - a Single input single output (SISO)
  - b MIMO systems and neural networks
- 6 Future ground-based interferometers

- **B Interferometers in Space**
  - 1 LISA: Laser Interferometer Space Antenna
  - 2 BBO: Big Bang observer
- **C Other Types of Gravitational Wave Detectors**
- **D Gravitational-Wave Data Analysis**
  - 1 Compact binary inspirals: matched filtering and template banks
  - 2 Continuous waves: doppler modulation, coverage of full sky
  - 3 GW background radiation: correlating multiple detectors
  - 4 Burst searches: various methods
  - 5 LISA data analysis

3rd Term of Ph236c

- ***Third Term: Ph236c --*** Taught by *Kip Thorne and Lee Lindblom*

  - A **Causal Structure of Spacetime:** Global hyperbolicity, event horizons, Cauchy horizons, chronology horizons. Cosmic censorship, topological censorship and Chronology protection. Dynamical black holes, wormholes and time machines
  - B **Singularities:** in exact solutions; singularity theorems; structure of generic singularities
  - **C General Relativity in Higher Dimensions**
    - 1 Our Universe as a Brane in a Higher Dimensional Bulk
  - **D Numerical Relativity in Depth**