Schedule of Lectures for "Singularities, Black Holes, Thermodynamics in Relativistic Spacetimes"

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course website:
http://strangebeautiful.com/lmu/2014-summer-sings-bhs-thermo.html

Summer, 2014
Mo. 12:00–14:00 C.T.
Ludwigstr. 31, 021

Contents

N.b.: many of the required and suggested readings are available online at the course's website, though they may not be listed as such in the bibliography:

http://strangebeautiful.com/lmu/2014-summer-sings-bhs-thermo.html

1 Week 1: Introduction to General Relativity; Differential Geometry I (Mar. 31)

a brief overview of general relativity, including the motiovation behind it (the principles of equivalence and general covariance, among other things); differential manifolds; vector fields; tensor analysis

Required Reading

1. Malament (2012, ch. 1, §§1–4), *Topics in the Foundations of General Relativity and Newtonian Gravitational Theory*
2. Wald (1984, chs. 1–2), *General Relativity*

Suggested Reading—Physics

1. Einstein (1915), "On the General Theory of Relativity"
2. Lorentz, Einstein, Minkowski, and Weyl (1952), *The Principle of Relativity*
3. Einstein (1984), *The Meaning of Relativity*
4. Anderson (1967, ch. 1, §§1–8, 10–11; ch. 4, §§1–3; ch. 10, §§1–3), *Principles of Relativity Physics*
5. Choquet-Bruhat (2009, ch. I, §§1–4; ch. III.1–4), *General Relativity and the Einstein Equations*
6. Eddington (1923, ch. I; ch. II, §§19–24), *Mathematical Theory of Relativity*
7. Hawking and Ellis (1973, ch. 1; ch. 2, §§1–2), *The Large Scale Structure of Space-Time*
8. Misner, Thorne, and Wheeler (1973, ch. 1; ch. 8, §§1–4; chs. 9, 16), *Gravitation*
9. Penrose and Rindler (1984, ch. 2, §§1–4; ch. 4, §1), *Spinors and Spacetime: Two-Spinor Calculus and Relativistic Fields*
10. Schrödinger (1950, chs. I-II), *Space-Time Structure*
11. Spivak (1965, chs. 1–2, 5), *Calculus on Manifolds*
12. Spivak (1979a, chs. 1–4, 7), *A Comprehensive Introduction to Differential Geometry*, vol. 1
13. Wald (1984, appendices A, C), *General Relativity*
14. Weyl (1921, ch. I, §§1–8; ch. II, §13), *Space-Time-Matter*
15. Will (1993, chs. 1–3, 7–8), *Theory and Experiment in Gravitational Physics*

Suggested Reading—Philosophy

1. Anderson (1962), "Absolute Change in General Relativity"
2. Brown (2005, appendix A), *Physical Relativity: Space-time Structure from a Dynamical Perspective*
3. Dicke (1962), "Mach's Principle and Equivalence"
4. Ehlers (1987), "Folklore in Relativity and What Is Really Known"
5. Gauss (1979), "General Investigations of Curved Surfaces"
6. Jammer (1961, chs. 5–13), *Concepts of Mass in Classical and Modern Physics*
7. Norton (1985), "What Was Einstein's Principle of Equivalence?"
8. Norton (1989), "How Einstein Found His Field Equations, 1912–1915"
9. Norton (1993), "General Covariance and the Foundations of General Relativity: Eight Decades of Dispute"
10. Russell (1997, chs. 8–15), *ABC of Relativity*
11. Sklar (1985), "Inertia, Gravitation, and Metaphysics"
12. Stachel (1989), "Einstein's Search for General Covariance, 1912–1915"
13. Stein (1977), "Some Philosophical Prehistory of General Relativity"

14. Synge (1960, preface; ch. 3), *Relativity: The General Theory*
15. Torretti (1996, ch. 5), *Relativity and Geometry*
16. Weyl (1921, ch. I, §§1–4; ch. II, §10), *Space-Time-Matter*
17. Weyl (1949, ch. III), *Philosophy of Mathematics and Natural Science*

2 Week 2: Differential Geometry II (Apr. 07)

diffeomorphisms; the Lie derivative; derivative operators; geodesics

Required Reading

1. Malament (2012, ch. 1, §§5–7), *Topics in the Foundations of General Relativity and Newtonian Gravitational Theory*
2. Wald (1984, ch. 3, §§1, 3), *General Relativity*

Suggested Reading—Physics

1. Anderson (1967, ch. 2), *Principles of Relativity Physics*
2. Choquet-Bruhat (2009, ch. I, §7), *General Relativity and the Einstein Equations*
3. Eddington (1923, ch. II, §§25–31), *Mathematical Theory of Relativity*
4. Hawking and Ellis (1973, ch. 2, §§4–5; ch. 4, §§1–2), *The Large Scale Structure of Space-Time*
5. Misner, Thorne, and Wheeler (1973, ch. 10), *Gravitation*
6. Penrose and Rindler (1984, ch. 4, §§2–3, 8), *Spinors and Spacetime: Two-Spinor Calculus and Relativistic Fields*
7. Schrödinger (1950, chs. III–V, VII), *Space-Time Structure*
8. Spivak (1979a, ch. 5), *A Comprehensive Introduction to Differential Geometry*, vol. 1
9. Spivak (1979b, chs. 4–7), *A Comprehensive Introduction to Differential Geometry*, vol. 2
10. Synge (1960, ch. 1, §§2–4), *Relativity: The General Theory*
11. Weyl (1921, ch. II, §14), *Space-Time-Matter*

3 Week 3: Differential Geometry III (Apr. 14)

curvature; (pseudo-)Riemannian metrics; hypersurfaces; volume elements

Required Reading

1. Malament (2012, ch. 1, §§8–11; ch. 2, §9), *Topics in the Foundations of General Relativity and Newtonian Gravitational Theory*
2. Wald (1984, ch. 3, §§2, 4), *General Relativity*

Suggested Reading—Physics

1. Anderson (1967, ch. 3), *Principles of Relativity Physics*
2. Choquet-Bruhat (2009, ch. I, §§5–6, 8–9), *General Relativity and the Einstein Equations*
3. Eddington (1923, ch. II, §§32–35), *Mathematical Theory of Relativity*
4. Ehlers, Pirani, and Schild (1972), "The Geometry of Free Fall and Light Propagation"
5. Hawking and Ellis (1973, ch. 2, §§6–8), *The Large Scale Structure of Space-Time*
6. Misner, Thorne, and Wheeler (1973, chs. 11, 13–15), *Gravitation*
7. Poisson (2004, ch. 3, §§1–4), *A Relativist's Toolkit: The Mathematics of Black-Hole Mechanics*
8. Schrödinger (1950, chs. VI, IX), *Space-Time Structure*

9. Spivak (1979a, chs. 6, 8–9), *A Comprehensive Introduction to Differential Geometry*, vol. 1
10. Synge (1960, ch. I, §§1, 5–10), *Relativity: The General Theory*
11. Weyl (1921, ch. II, §§11–12, 15–18), *Space-Time-Matter*

Suggested Reading—Philosophy

1. Helmholtz (1870), "On the Origin and Significance of the Geometrical Axioms"
2. Riemann (1854), "On the Hypotheses, Which Lie at the Basis of Geometry"
3. Spivak (1979b, §4.B), *A Comprehensive Introduction to Differential Geometry*, vol. 2

4 Week 4: General Relativity, The Core (Apr. 21)

relativistic spacetime; stress-energy and the Einstein field-equation; Killing fields (isometries); conserved quantities

Required Reading

1. Malament (2012, ch. 2, §§1–5, 7, 9), *Topics in the Foundations of General Relativity and Newtonian Gravitational Theory*
2. Wald (1984, ch. 4, §§1–3), *General Relativity*

Suggested Reading—Physics

1. Anderson (1967, ch. 10, §§4–8), *Principles of Relativity Physics*
2. Choquet-Bruhat (2009, ch. III, §§5–10), *General Relativity and the Einstein Equations*
3. Eddington (1923, chs. 3–4; ch. 5, §§65–69), *Mathematical Theory of Relativity*
4. Ehlers, Pirani, and Schild (1972), "The Geometry of Free Fall and Light Propagation"
5. Hawking and Ellis (1973, ch. 3; ch. 4, §§1–3), *The Large Scale Structure of Space-Time*
6. Misner, Thorne, and Wheeler (1973, chs. 16–17, 20), *Gravitation*
7. Penrose (1967), "Conserved Quantities and Conformal Structure in General Relativity"
8. Penrose (1968), "Structure of Spacetime"
9. Pirani (1962), "Gauss's Theorem and Gravitational Energy"
10. Poisson (2004, ch. 2, §1), *A Relativist's Toolkit: The Mathematics of Black-Hole Mechanics*
11. Schrödinger (1950, chs. X–XI), *Space-Time Structure*
12. Synge (1957, chs. I–IV), *The Relativistic Gas*
13. Synge (1960, chs. III–IV), *Relativity: The General Theory*
14. Synge (1962), "Tensorial Integral Conservation Laws in General Relativity"
15. Trautman (1962), "Conservation Laws in General Relativity"
16. Trautman (1965), "Foundations and Current Problems of General Relativity"
17. Weyl (1921, ch. III, §§19, 21–22, 24–25), *Space-Time-Matter*

Suggested Reading—Philosophy

1. Belot (1996), "Why General Relativity *Does* Need an Interpretation"
2. Belot (2005), "Dust, Time and Symmetry"
3. Bergmann (1977), "Geometry and Observables"
4. Brown (2005, ch. 9), *Physical Relativity: Space-time Structure from a Dynamical Perspective*
5. Curiel (2000), "The Constraints General Relativity Places on Physicalist Accounts of Causality"
6. Curiel (2009), "General Relativity Needs No Interpretation"
7. Curiel (2013), "On Tensorial Concomitants and the Non-Existence of a Gravitational Stress-Energy Tensor"

8. Curiel (2014d), "A Primer on Energy Conditions"
9. DiSalle (2006, ch. 4, §§4–7), *Understanding Space-Time*
10. Earman (1989, ch. 9), *World Enough and Space-Time*
11. Earman and Norton (1987), "What Price Spacetime Substantivalism? The Hole Story"
12. Eddington (1920, chs. V–XII), *Space, Time & Gravitation: An Outline of the General Theory of Relativity*
13. Friedman (1983, chs.II, V–VII), *Foundations of Space-Time Theories*
14. Geroch (1981, chs. 7–8), *General Relativity from A to B*
15. Hoefer (2000), "Energy Conservation in GTR"
16. Malament (2002), "A No-Go Theorem About Rotation in Relativity Theory"
17. Malament (2003), "On Relative Orbital Rotation in General Relativity"
18. Møller (1962), "The Energy-Momentum Complex in General Relativity and Related Problems"
19. Reichenbach (1958, ch. IIIB), *Philosophy of Space and Time*
20. Rovelli (1991), "What Is Observable in Classical and Quantum Gravity?"
21. Rovelli (2000), "Quantum Spacetime: What Do We Know?"
22. Rovelli (2002), "GPS Observables in General Relativity"
23. Sklar (1976, ch. 3), *Space, Time and Spacetime*
24. Torretti (1996, ch. 6), *Relativity and Geometry*

5 Week 5: Causal Structure (Apr. 28)

orientability; causality conditions and closed timelike curves; domains of dependence and causal horizons; global hyperbolicity

Required Reading

1. Hawking and Ellis (1973, ch. 6), *The Large Scale Scale Structure of Space-time*
2. Geroch (1977b), "Prediction in General Relativity"
3. Geroch and Horowitz (1979), "Global Structure of Spacetimes", pp. 212–255 (through §5.2) and the appendix
4. Manchak (2009a), "Can We Know the Global Structure of Spacetime?"
5. Wald (1984, ch. 8), *General Relativity*

Suggested Reading—Physics

1. Carter (1971b), "Causal Structure in Space-Time"
2. Choquet-Bruhat (2009, ch. 12), *General Relativity and the Einstein Equations*
3. Ehlers, Pirani, and Schild (1972), "The Geometry of Free Fall and Light Propagation"
4. Garcia-Parrado and Senovilla (2005), "Causal Structures and Causal Boundaries"
5. Geroch (1970a), "Domain of Dependence"
6. Geroch (1971a), "General Relativity in the Large"
7. Geroch (1971b), "Space-Time Structure from a Global Viewpoint"
8. Geroch, Kronheimer, and Penrose (1972), "Ideal Points in Space-time"
9. S. (1968), "The Existence of Cosmic Time Functions"
10. Hawking (1986), "Chronology Protection Conjecture"
11. Joshi (1993, ch. 4), *Global Aspects in Gravitation and Cosmology*
12. Kronheimer and Penrose (1967), "On the Structure of Causal Spaces"
13. Joshi (1993, ch. 4), *Global Aspects in Gravitation and Cosmology*
14. Misner (1967), "Taub-NUT Space As a Counterexample to Almost Anything"

15. Penrose (1968), "Structure of Spacetime"
16. Penrose (1972), *Techniques of Differential Topology in Relativity*

Suggested Reading—Philosophy

1. Curiel (2014c), "On the Existence of Spacetime Structure"
2. Earman (1995, chs. 5–7), *Bangs, Crunches, Whimpers and Shrieks: Singularities and Acausalities in Relativistic Spacetimes*
3. Earman, Smeenk, and Wüthrich (2009), "Do the Laws of Physics Forbid the Operation of Time Machines?"
4. Glymour (1977), "Indistinguishable Space-Times and the Fundamental Group"
5. Malament (1977a), "The Class of Continuous Timelike Curves Determines the Topology of Spacetime"
6. Malament (1977b), "Observationally Indistinguishable Spacetimes: Comments on Glymour's Paper"
7. Manchak (2008), "Is Prediction Possible in General Relativity?"
8. Manchak (2009a), "Can We Know the Global Structure of Spacetime?"
9. Manchak (2009b), "Is Spacetime Hole-Free?"
10. Manchak (2009c), "On the Existence of 'Time Machines' in General Relativity"
11. Manchak (2011a), "No No-Go: A Remark on Time Machines"
12. Manchak (2011b), "What Is a Physically Reasonable Spacetime?"

6 Week 6: Singularities, I (May 05)

geodesic congruences and the Raychaudhuri equation; conjugate points; incomplete curves; extensions of spacetimes

Required Reading

1. Hawking and Ellis (1973, ch. 4, §§4–5), *The Large Scale Structure of Space-Time*
2. Wald (1984, ch. 9, §§1–4), *General Relativity*

Suggested Reading—Physics

1. Choquet-Bruhat (2009, ch. 13, §§1–3), *General Relativity and the Einstein Equations*
2. Clarke (1973), "Local Extensions in Singular Spacetimes"
3. Clarke (1993), *The Analysis of Space-Time Singularities*
4. Joshi (1993, ch. 5), *Global Aspects in Gravitation and Cosmology*
5. Joshi (2007), *Gravitational Collapse and Spacetime Singularities*
6. Poisson (2004, ch. 2, §§3–4), *A Relativist's Toolkit: The Mathematics of Black-Hole Mechanics*

Suggested Reading—Philosophy

1. Earman (1995, chs. 1–4), *Bangs, Crunches, Whimpers and Shrieks: Singularities and Acausalities in Relativistic Spacetimes*
2. Manchak (2012), "On the Relationship between Spacetime Singularities, Holes, and Extensions"

7 Week 7: Singularities, II (May 12)

possible definitions of a singularity; the Geroch-Hawking-Penrose theorems; naked singularities and cosmic censorship

Required Reading

1. Curiel (1999), "The Analysis of Singular Spacetimes"
2. Geroch (1968c), "What Is a Singularity in General Relativity?"
3. Geroch and Horowitz (1979), "Global Structure of Spacetimes", pp. 255–293
4. Wald (1984, ch. 9, §5), *General Relativity*

Original Literature

1. Geroch (1966), "Singularities in Closed Universes"
2. Geroch (1968a), "Local Characterization of Singularities in General Relativity"
3. Geroch (1968b), "The Structure of Singularities"
4. Geroch (1970b), "Singularities"
5. Hawking (1965), "Occurrence of Singularities in Open Universes"
6. Hawking (1966a), "The Occurrence of Singularities in Cosmology"
7. Hawking (1966b), "The Occurrence of Singularities in Cosmology. II"
8. Hawking (1966c), "Singularities in the Universe"
9. Hawking (1967), "The Occurrence of Singularities in Cosmology. III: Causality and Singularities"
10. Hawking and Ellis (1965), "Singularities in Homogeneous World Models"
11. Hawking and Ellis (1969), "The Cosmic Black Body Radiation and the Existence of Singularities in Our Universe"
12. Hawking and Penrose (1970), "The Singularities of Gravitational Collapse and Cosmology"
13. Penrose (1965), "Gravitational Collapse and Space-time Singularities"
14. Penrose (1969), "Gravitational Collapse: The Role of General Relativity"

Suggested Reading—Physics

1. Borde (1987), "Geodesic Focusing, Energy Conditions and Singularities"
2. Bosshard (1976), "On the b-Boundary of the Closed Friedmann Model"
3. Bosshard (1979), "On b-Boundaries of Special Space-Time Models"
4. Choquet-Bruhat (2009, ch. XIII, §§4–5, 7), *General Relativity and the Einstein Equations*
5. Clarke (1975b), "Singularities in Globally Hyperbolic Spacetimes"
6. Clarke (1976), "Space-Time Singularities"
7. Clarke (1979a), "Boundary Definitions"
8. Clarke (1993), *The Analysis of Space-Time Singularities*
9. Clarke and Królak (1985), "Conditions for the Occurrence of Strong Curvature Singularities"
10. Clarke and Schmidt (1977), "Singularities: The State of the Art"
11. Ellis and Schmidt (1977), "Singular Space-times"
12. Fewster and Galloway (2011), "Singularity Theorems from Weakened Energy Conditions"
13. Galloway and Horta (1996), "Regularity of Lorentzian Busemann Functions"
14. Gannon (1975), "Singularities in Nonsimply Connected Space-Times"
15. Geroch (1983), "The Local Nonsingularity Theorem"
16. Geroch, Can-bin, and Wald (1982), "Singular Boundaries of Spacetimes"
17. Hawking and Ellis (1973, ch. 8), *The Large Scale Structure of Space-Time*
18. Johnson (1977), "The Bundle Boundary in Some Special Cases"
19. Johnson (1979), "The Bundle Boundary for the Schwarzschild and Friedmann Solutions"
20. Joshi (1993, chs. 6–7), *Global Aspects in Gravitation and Cosmology*
21. Joshi (2007, ch. 4), *Gravitational Collapse and Spacetime Singularities*
22. King (1974), "New Types of Singularity in General Relativity: The General Cylindrically Symmetric Stationary Dust Solution"

23. Konkowski and Helliwell (1992), "Singularities in Colliding Plane-Wave Spacetimes"
24. Roman (1988), "On the 'Averaged Weak Energy Condition' and Penrose's Singularity Theorem"
25. Schmidt (1971), "A New Definition of Singular Points in General Relativity"
26. Senovilla (1997), "Singularity Theorems and Their Consequences"
27. Senovilla (2007), "A Singularity Theorem Based on Spatial Averages"
28. Senovilla (2008), "A New Type of Singularity Theorem"
29. Siklos (1979), "Singularities and Invariants"
30. Siklos (1981), "Nonscalar Singularities in Spatially Homogeneous Cosmologies"
31. Thorpe (1977), "Curvature Invariants and Space-Time Singularities"
32. Tipler (1977a), "Singularities and Causality Violations"
33. Tipler (1977b), "Singularities in Conformally Flat Spacetimes"
34. Tipler (1978), "Energy Conditions, and Spacetime Singularities"
35. Tipler (1979), "The Growth of Curvature Near a Space-Time Singularity"
36. Tipler, Clarke, and Ellis (1980), "Singularities and Horizons—A Review Article"

Suggested Reading—Philosophy

1. Clarke (1975a), "The Classification of Singularities"
2. Clarke (1979b), "The Nature of Singularities"
3. Earman (1995, chs. 1–4), *Bangs, Crunches, Whimpers and Shrieks: Singularities and Acausalities in Relativistic Spacetimes*
4. Earman and Eisenstaedt (1999), "Einstein and Singularities"
5. Ellis and Schmidt (1979), "Classification of Singular Spacetimes"
6. Hawking and Penrose (1996, ch. 2), *The Nature of Space and Time*
7. Joshi (2003), "Cosmic Censorship: A Current Perspective"
8. Manchak (2012), "On the Relationship between Spacetime Singularities, Holes, and Extensions"
9. Penrose (1973), "Naked Singularities"
10. Penrose (1979), "Singularities and Time-Asymmetry"
11. Penrose (1998), "The Question of Cosmic Censorship"
12. Taub (1979), "Remarks on the Symposium on Singularities"

8 Week 8–9: Schwarzschild and Kerr Spacetimes (May 19, May 26)

isolated systems; sphericity, staticity, stationarity, axisymmetry; derivation of the metrics; Birkhoff's Theorem; Lense-Thirring effect; Penrose process

Required Reading

1. Hawking and Ellis (1973, ch. 5, §§5–6), *The Large Scale Structure of Space-Time*
2. Wald (1984, ch. 6; ch. 12, §§3–4), *General Relativity*

Suggested Reading—Physics

1. Anderson (1967, ch. 10, §5; ch. 11, §§3–4), *Principles of Relativity Physics*
2. Bekenstein (1973b), "Extraction of Energy and Charge from a Black Hole"
3. Carter (1968), "Global Structure of the Kerr Family of Gravitational Fields"
4. Carter (1969), "Killing Horizons and Orthogonally Transitive Groups in Space-Time"

5. Chandrasekhar (1983, chs. 3, 6), *The Mathematical Theory of Black Holes*
6. Choquet-Bruhat (2009, ch. IV, §§1–12; ch. XIV, §§3, 7–9), *General Relativity and the Einstein Equations*
7. Geroch (1973), "Energy Extraction"
8. Griffiths and Podolský (2009, chs. 8, 11), *Exact Space-Times in Einstein's General Relativity*
9. Kerr (1963), "Gravitational Field of a Spinning Mass as an Example of Algebraically Special Metrics"
10. Misner, Thorne, and Wheeler (1973, chs. 23–25, 31–32), *Gravitation*
11. Penrose (1969), "Gravitational Collapse: The Role of General Relativity"
12. Penrose and Floyd (1971), "Extraction of Rotational Energy from a Black Hole"
13. Poisson (2004, ch. 5, §§1, 3), *A Relativist's Toolkit: The Mathematics of Black-Hole Mechanics*
14. Rindler (2006, ch. 11), *Relativity: Special, General and Cosmological*
15. Synge (1960, ch. VII), *Relativity: The General Theory*

Suggested Reading—Philosophy

1. Harper (2007), "Newton's Methodology and Mercury's Perihelion before and after Einstein"
2. Harper (2011, ch. 10), *Isaac Newton's Scientific Method: Turning Data Into Evidence about Gravity and Cosmology*
3. Israel (1987), "Dark Stars: The Evolution of an Idea"
4. Malament (2002), "A No-Go Theorem About Rotation in Relativity Theory"
5. Malament (2003), "On Relative Orbital Rotation in General Relativity"
6. Penrose (1980), "On Schwarzschild Causality—A Problem for 'Lorentz Covariant' General Relativity"

9 Week 10: Black Holes (Jun. 02)

conformal infinity; trapped surfaces and event horizons; asymptotically flat black holes; uniqueness theorems

Required Reading

1. Hawking and Ellis (1973, ch. 9), *The Large Scale Structure of Space-Time*
2. Wald (1984, ch. 11, §1; ch. 12, §§1–2), *General Relativity*

Original Literature

1. Bekenstein (1972b), "Nonexistence of Baryon Number for Static Black Holes"
2. Carter (1971a), "Axisymmetric Black Hole Has Only Two Degrees of Freedom"
3. Carter (1973), "Black Hole Equilibrium States"
4. Geroch (1971b), "Space-Time Structure from a Global Viewpoint"
5. Geroch (1972), "Structure of the Gravitational Field at Spatial Infinity"
6. Geroch (1977a), "Asymptotic Structure of Space-Time"
7. Hawking (1972), "Black Holes in General Relativity"
8. Hawking (1973), "The Event Horizon"
9. Israel (1967), "Event Horizons in Static Vacuum Space-Times"
10. Müller zum Hagen, Robinson, and Seifert (1973), "Black holes in Static Vacuum Space-Times"
11. Penrose (2011), "Conformal Treatment of Infinity"
12. Penrose (1965), "Gravitational Collapse and Space-Time Singularities"

13. Penrose (1968), "Structure of Spacetime"
14. Penrose (1969), "Gravitational Collapse: The Role of General Relativity"
15. Robinson (1975), "Uniqueness of the Kerr Black Hole"
16. Robinson (1977), "A Simple Proof of the Generalization of Israel's Theorem"
17. Teitelboim (1972a), "Nonmeasurability of the Lepton Number of a Black Hole"
18. Teitelboim (1972b), "Nonmeasurability of the Quantum Numbers of a Black Hole"
19. Wald (1972), "Electromagnetic Fields and Massive Bodies"
20. Wald (1973), "On Perturbations of a Kerr Black Hole"

Suggested Reading—Physics

1. Ansoldi (2007), "Spherical Black Holes with Regular Center: A Review of Existing Models Including A Recent Realization with Gaussian Sources"
2. Ashtekar (2003), "How Black Holes Grow"
3. Carter (1979), "The General Theory of the Mechanical, Electromagnetic and Thermodynamic Properties of Black Holes"
4. Carter (1999), "The Black Hole Equilibrium Problem"
5. Choquet-Bruhat (2009, ch. XIV, §§1–3, 7–10), *General Relativity and the Einstein Equations*
6. Christodoulou (2009), *The Formation of Black Holes in General Relativity*
7. Geroch and Hartle (1982), "Distorted Black Holes"
8. Heusler (1996), *Black Hole Uniqueness Theorems*
9. Joshi (2007, ch. 5), *Gravitational Collapse and Spacetime Singularities*
10. Misner, Thorne, and Wheeler (1973, chs. 33–34), *Gravitation*
11. Poisson (2004, ch. 5, §4), *A Relativist's Toolkit: The Mathematics of Black-Hole Mechanics*
12. Schoen and Yau (1983), "The Existence of a Black Hole Due to Condensation of Matter"

10 Week 11: The Laws of Black Hole Mechanics (Jun. 09)

the four law of black hole mechanics; my birthday!

Required Reading

1. Bardeen, Carter, and Hawking (1973), "The Four Laws of Black Hole Mechanics"
2. Israel (1986), "Third Law of Black Hole Mechanics: A Formulation of a Proof"
3. Wald (1984, ch. 12, §5), *General Relativity*
4. Wald and Gao (2001), "'Physical Process Version' of the First Law and the Generalized Second Law for Charged and Rotating Black Holes"

Suggested Reading—Physics

1. Carter (1979), "The General Theory of the Mechanical, Electromagnetic and Thermodynamic Properties of Black Holes"
2. Hawking (1971), "Gravitational Radiation from Colliding Black Holes"
3. Hawking (1972), "Black Holes in General Relativity"
4. Hayward (1994), "General Laws of Black Hole Dynamics"
5. Hayward (2006), "Conservation Laws for Dynamical Black Holes"
6. Poisson (2004, ch. 5, §5), *A Relativist's Toolkit: The Mathematics of Black-Hole Mechanics*
7. Thorne, Price, and MacDonald (1986), *Black Holes: The Membrane Paradigm*
8. Wald (1997), "'Nernst Theorem' and Black Hole Thermodynamics"

Suggested Reading—Philosophy

1. Hawking and Penrose (1996, ch. 1), *The Nature of Space and Time*

11 Week 12: Black Holes and Thermodynamics (Jun. 16)

the thermodynamical character of black holes

Required Reading

1. Curiel (2014a), "Classical Black Holes Are Hot"
2. Wald (1994, ch. 6), *Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics*
3. Wald (1999b), "The Thermodynamics of Black Holes"

Original Literature

1. Bekenstein (1972a), "Black Holes and the Second Law"
2. Bekenstein (1973a), "Black Holes and Entropy"
3. Bekenstein (1974), "Generalized Second Law of Thermodynamics in Black-Hole Physics"
4. Christodoulou (1970), "Reversible and Irreversible Transformations in General Relativity"
5. Hawking (1974), "Black Hole Explosions?"
6. Hawking (1975), "Particle Creation by Black Holes"
7. Hawking (1976a), "Black Holes and Thermodynamics"
8. Israel (1973), "Entropy and Black Hole Dynamics"
9. Sciama (1976), "Black Holes and Their Thermodynamics"

Suggested Reading—Physics

1. Bekenstein (1983), "Entropy Bounds and the Second Law for Black Holes"
2. Bekenstein (1994), "Do We Understand Black Hole Entropy?"
3. Bekenstein (1999), "Non-Archimedean Character of Quantum Buoyancy and the Generalized Second Law of Thermodynamics"
4. Flanagan, Marolf, and Wald (2000), "Proof of Classical Versions of the Bousso Entropy Bound and of the Generalized Second Law"
5. Israel (1992), "Thermodynamics and Internal Dynamics of Black Holes: Some Recent Developments"
6. Israel (1998), "Gedanken Experiments in Black Hole Mechanics"
7. Jacobson (1999), "On the Nature of Black Hole Entropy"
8. Jacobson, Marolf, and Rovelli (2005), "Black Hole Entropy: Inside or Out?"
9. Jacobson and Parentani (2003), "Horizon Entropy"
10. Thorne, Price, and MacDonald (1986), *Black Holes: The Membrane Paradigm*
11. Unruh and Wald (1982), "Acceleration Radiation and the Generalized Second Law of Thermodynamics"
12. Wald (1993), "Black Hole Entropy Is the Noether Charge"
13. Wald (1997), "'Nernst Theorem' and Black Hole Thermodynamics"

Suggested Reading—Philosophy

1. Hawking and Penrose (1996, chs. 3–4), *The Nature of Space and Time*
2. Sorkin (2005), "Ten Theses on Black Hole Entropy"
3. Wald (1999a), "Gravitation, Thermodynamics and Quantum Theory"

12 Week 13: Hawking Radiation (Jun. 23)

Hawking radiation; black-hole evaporation; information loss; non-unitary evolution

Required Reading

1. Wald (1994, chs. 5, 7), *Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics*

Suggested Reading—Physics

1. Balasubramanian, Marolf, and Rozali (2006), "Information Recovery from Black Holes"
2. Banks, Susskind, and Peskind (1984), "Difficulties for the Evolution of Pure States into Mixed States"
3. Davies and Taylor (1974), "Do Black Holes Really Explode?"
4. Fredenhagen and Haag (1990), "On the Derivation of the Hawking Radiation Associated with the Formation of a Black Hole"
5. Hartle (1994), "Spacetime Information"
6. Hartle (1998), "Generalized Quantum Theory in Evaporating Black Hole Spacetimes"
7. Hartle and Hawking (1976), "Path-Integral Derivation of Black Hole Radiance"
8. Hawking (1974), "Black Hole Explosions?"
9. Hawking (1975), "Particle Creation by Black Holes"
10. Hawking (1976a), "Black Holes and Thermodynamics"
11. Hawking (1976b), "Breakdown of Predictability in Gravitational Collapse"
12. Hawking (1998), "Loss of Information in Black Holes"
13. Hawking (2005), "Information Loss in Black Holes"
14. Jacobson (2003), "Introduction to Quantum Fields in Curved Spacetime and the Hawking Effect"
15. Page (1980), "Is Black-Hole Evaporation Predictable?"
16. Wald (1984, ch. 14, §§2–4), *General Relativity*

Suggested Reading—Philosophy

1. Bekenstein (2000), "The Limits of Information"
2. Belot, Earman, and Ruetsche (1999), "The Hawking Information Loss Paradox: The Anatomy of Controversy"
3. Hawking and Penrose (1996), *The Nature of Space and Time*
4. Hayward (2005), "The Dis-Information Problem for Black Holes (Conference Version)"
5. Page (2005), "Hawking Radiation and Black Hole Thermodynamics"

13 Week 14: Basic Cosmology (Jun. 30)

homogeneity and isotropy; derivation of the FLRW spacetimes and their properties; dark energy and the cosmological constant

Required Reading

1. Malament (2012, §2.11), *Topics in the Foundations of General Relativity and Newtonian Gravitational Theory*
2. Wald (1984, ch. 5), *General Relativity*

Suggested Reading—Physics

1. Anderson (1967, ch. 14), *Principles of Relativity Physics*
2. Bekenstein (1975), "Nonsingular General-Relativistic Cosmologies"
3. Cattoën and Visser (2008), "Cosmodynamics: Energy Conditions, Hubble Bounds, Density Bounds, Time and Distance Bounds"
4. Choquet-Bruhat (2009, ch. V), *General Relativity and the Einstein Equations*
5. Ellis, Maartens, and MacCallum (2012, chs. 5–9, 13–14, 17–19), *Relativistic Cosmology*
6. Griffiths and Podolský (2009, chs. 4–6; ch. 22, §§1–2, 7–8), *Exact Space-Times in Einstein's General Relativity*
7. Hawking and Ellis (1973, ch. 5, §§2—4, 7), *The Large Scale Structure of Space-Time*
8. Joshi (1993, ch. 8), *Global Aspects in Gravitation and Cosmology*
9. Krasiński (2006, chs. 1–3, 6), *Inhomogeneous Cosmological Models*
10. Malament (2012, ch. 3, §1), *Topics in the Foundations of General Relativity and Newtonian Gravitational Theory*
11. Misner, Thorne, and Wheeler (1973, chs. 27–30), *Gravitation*
12. Ellis and Sciama (1972), "Global and Non-Global Problems in Cosmology"
13. Shepley and Ryan (1978), *Homogeneous Cosmological Models*
14. Stephani, Kramer, MacCallum, Hoenselaers, and Herlt (2009, chs. 13–14, 23), *Exact Solutions of Einstein's Field Equations*
15. Visser (1997a), "Energy Conditions in the Epoch of Galaxy Formation"
16. Visser (1997b), "General Relativistic Energy Conditions: The Hubble Expansion in the Epoch of Galaxy Formation"
17. Visser (2005), "Cosmography: Cosmology without the Einstein Equation"
18. Weinberg (1972, ch. 14, §§1–6), *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*
19. Weinberg (2008, ch. 1, §§1–7; ch. 3, §1; ch. 4), *Cosmology*

Suggested Reading—Philosophy

1. Bondi (1955), "Fact and Inference in Theory and in Observation"
2. Curiel (2014b), "Energy Conditions and Cosmology"
3. Dicke and Peebles (1979), "The Big Bang Cosmology—Enigmas and Nostrums"
4. Ellis (2007), "Issues in the Philosophy of Cosmology"
5. Harper (2011, ch. 10, §5), *Isaac Newton's Scientific Method: Turning Data Into Evidence about Gravity and Cosmology*
6. Munitz (1962), "The Logic of Cosmology"
7. Penrose (1989), "Difficulties with Inflationary Cosmology"
8. Smeenk (2012a), "Inflation and the Origin of Structure"
9. Smeenk (2012b), "The Logic of Cosmology Revisited"
10. Smeenk (2012c), "Philosophy of Cosmology"

14 Week 15: Cosmological Singularities and Thermodynamics (Jul. 07)

the initial-state problem; Penrose's Weyl Curvature Hypothesis; sudden singularities; possible measures of gravitational entropy

Required Reading

1. Barrow (2004b), "Sudden Future Singularities"
2. Clifton, Ellis, and Tavakol (2013), "A Gravitational Entropy Proposal"
3. Newman (1993), "On the Structure of Conformal Singularities in Classical General Relativity"
4. Penrose (1979), "Singularities and Time-Asymmetry"
5. Wallace (2010), "Gravity, Entropy, and Cosmology: In Search of Clarity"

Suggested Reading—Physics

1. Barrow (2004a), "More General Sudden Singularities"
2. Caldwell (2002), "A Phantom Menace? Cosmological Consequences of a Dark Energy Component with Super-Negative Equation of State"
3. Caldwell, Kamionkowski, and Weinberg (2003), "Phantom Energy: Dark Energy with $w < -1$ Causes a Cosmic Doomsday"
4. Cattoën and Visser (2005), "Necessary and Sufficient Conditions for Big Bangs, Bounces, Crunches, Rips, Sudden Singularities and Extremality Events"
5. Cattoën and Visser (2007), "Cosmological Milestones and Energy Conditions"
6. Chimento and Lazkoz (2004), "On Big Rip Singularities"
7. Cotsakis and Klaoudatou (2007), "Cosmological Singularities and Bel-Robinson Energy"
8. Dabrowski, Stachowiak, and Szydłowski (2003), "Phantom Cosmologies"
9. Dabrowski and Denkiewicz (2009), "Barotropic Index w-Singularities in Cosmology"
10. L. and Lazkoz (2006), "Classification of Cosmological Milestones"
11. Goode and Wainwright (1985), "Isotropic Singularities in Cosmological Models"
12. Tod (2002), "Isotropic Cosmological Singularities"

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Balasubramanian, V., D. Marolf, and M. Rozali (2006). Information recovery from black holes. arXiv:hep-th/0604045v3.

Banks, T., L. Susskind, and M. Peskind (1984). Difficulties for the evolution of pure states into mixed states. *Nuclear Physics B 244*, 125–134.

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Barrow, J. (2004b). Sudden future singularities. *Classical and Quantum Gravity 21*(11), L79–L82. doi:10.1088/0264-9381/21/11/L03.

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