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. 12:10–14:00 (real time)
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 (Apr. 07)

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

Required Reading

1. Malament (2012, ch. 1, §§1–2), *Topics in the Foundations of General Relativity and Newtonian Gravitational Theory*
2. Wald (1984, ch. 1; ch. 2, §1), *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. 14)

tangent vectors; vector fields; integral curves; cotangent vectors

Required Reading

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

Suggested Reading—Physics

1. Anderson (1967, chs. 2–3), *Principles of Relativity Physics*
2. Choquet-Bruhat (2009, ch. I, §§5–7, 8–9), *General Relativity and the Einstein Equations*
3. Eddington (1923, ch. II, §§25–35), *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, §§4–8; ch. 4, §§1–2), *The Large Scale Structure of Space-Time*
6. Misner, Thorne, and Wheeler (1973, chs. 10–11, 13–15), *Gravitation*
7. Penrose and Rindler (1984, ch. 4, §§2–3, 8), *Spinors and Spacetime: Two-Spinor Calculus and Relativistic Fields*
8. Poisson (2004, ch. 3, §§1–4), *A Relativist's Toolkit: The Mathematics of Black-Hole Mechanics*
9. Schrödinger (1950, chs. III–VII, IX), *Space-Time Structure*
10. Spivak (1979a, chs. 5–6, 8–9), *A Comprehensive Introduction to Differential Geometry*, vol. 1
11. Spivak (1979b, chs. 4–7), *A Comprehensive Introduction to Differential Geometry*, vol. 2
12. Synge (1960, ch. I, §§1–10), *Relativity: The General Theory*
13. Weyl (1921, ch. II, §§11–12, 14–18), *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

3 Week 3: HOLIDAY: NO LECTURE (Apr. 21)

4 Week 4: Differential Geometry III (Apr. 28)

abstract-index notation; tensor analysis; diffeomorphisms; action of diffeomorphisms on tensors

Required Reading

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

Suggested Reading—Physics

1. Anderson (1967, chs. 2–3), *Principles of Relativity Physics*
2. Choquet-Bruhat (2009, ch. I, §§5–7, 8–9), *General Relativity and the Einstein Equations*
3. Eddington (1923, ch. II, §§25–35), *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, §§4–8; ch. 4, §§1–2), *The Large Scale Structure of Space-Time*
6. Misner, Thorne, and Wheeler (1973, chs. 10–11, 13–15), *Gravitation*
7. Penrose and Rindler (1984, ch. 4, §§2–3, 8), *Spinors and Spacetime: Two-Spinor Calculus and Relativistic Fields*
8. Poisson (2004, ch. 3, §§1–4), *A Relativist's Toolkit: The Mathematics of Black-Hole Mechanics*
9. Schrödinger (1950, chs. III–VII, IX), *Space-Time Structure*
10. Spivak (1979a, chs. 5–6, 8–9), *A Comprehensive Introduction to Differential Geometry*, vol. 1
11. Spivak (1979b, chs. 4–7), *A Comprehensive Introduction to Differential Geometry*, vol. 2
12. Synge (1960, ch. I, §§1–10), *Relativity: The General Theory*
13. Weyl (1921, ch. II, §§11–12, 14–18), *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

5 Week 5: Differential Geometry IV (May 05)

the Lie derivative; derivative operators; geodesics; curvature; (pseudo-)Riemannian metrics

Required Reading

1. Malament (2012, ch. 1, §§6–9), *Topics in the Foundations of General Relativity and Newtonian Gravitational Theory*
2. Wald (1984, ch. 3, §4; 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*

6 Week 6: General Relativity, The Core (May 12)

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

Required Reading

1. Malament (2012, ch. 1, §§9–11; ch. 2, §§1–5, 7, 9), *Topics in the Foundations of General Relativity and Newtonian Gravitational Theory*
2. Wald (1984, ch. 3, §4; 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*

7 Week 7: Causal Structure (May 19)

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?"

8 Week 8: Singularities, I (May 26)

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"

9 Week 9: Singularities, II (Jun. 02)

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"

10 Week 10: HOLIDAY: NO LECTURE (Jun. 09)

my birthday!

11 Week 11: Schwarzschild and Kerr Spacetimes; Black Holes (Jun. 16)

isolated systems; sphericity, staticity, stationarity, axisymmetry; derivation of the metrics; Birkhoff's Theorem; Lense-Thirring effect; Penrose process; conformal infinity; trapped surfaces and event horizons; asymptotically flat black holes; uniqueness theorems

Required Reading

1. Hawking and Ellis (1973, ch. 5, §§5–6; ch. 9), *The Large Scale Structure of Space-Time*

2. Wald (1984, ch. 6; ch. 11, §1; ch. 12), *General Relativity*

Original Literature

1. Bekenstein (1972b), "Nonexistence of Baryon Number for Static Black Holes"
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. Carter (1971a), "Axisymmetric Black Hole Has Only Two Degrees of Freedom"
6. Carter (1973), "Black Hole Equilibrium States"
7. Geroch (1971b), "Space-Time Structure from a Global Viewpoint"
8. Geroch (1972), "Structure of the Gravitational Field at Spatial Infinity"
9. Geroch (1977a), "Asymptotic Structure of Space-Time"
10. Hawking (1972), "Black Holes in General Relativity"
11. Hawking (1973), "The Event Horizon"
12. Israel (1967), "Event Horizons in Static Vacuum Space-Times"
13. Kerr (1963), "Gravitational Field of a Spinning Mass as an Example of Algebraically Special Metrics"
14. Müller zum Hagen, Robinson, and Seifert (1973), "Black holes in Static Vacuum Space-Times"
15. Penrose (2011), "Conformal Treatment of Infinity"
16. Penrose (1965), "Gravitational Collapse and Space-Time Singularities"
17. Penrose (1968), "Structure of Spacetime"
18. Penrose (1969), "Gravitational Collapse: The Role of General Relativity"
19. Penrose and Floyd (1971), "Extraction of Rotational Energy from a Black Hole"
20. Robinson (1975), "Uniqueness of the Kerr Black Hole"
21. Robinson (1977), "A Simple Proof of the Generalization of Israel's Theorem"
22. Teitelboim (1972a), "Nonmeasurability of the Lepton Number of a Black Hole"
23. Teitelboim (1972b), "Nonmeasurability of the Quantum Numbers of a Black Hole"
24. Wald (1972), "Electromagnetic Fields and Massive Bodies"
25. Wald (1973), "On Perturbations of a Kerr Black Hole"

Suggested Reading—Physics

1. Anderson (1967, ch. 10, §5; ch. 11, §§3–4), *Principles of Relativity Physics*
2. Ansoldi (2007), "Spherical Black Holes with Regular Center: A Review of Existing Models Including A Recent Realization with Gaussian Sources"
3. Ashtekar (2003), "How Black Holes Grow"
4. Carter (1979), "The General Theory of the Mechanical, Electromagnetic and Thermodynamic Properties of Black Holes"
5. Carter (1999), "The Black Hole Equilibrium Problem"
6. Chandrasekhar (1983, chs. 3, 6), *The Mathematical Theory of Black Holes*
7. Choquet-Bruhat (2009, ch. IV, §§1–12; ch. XIV, §§1–3, 7–10), *General Relativity and the Einstein Equations*
8. Christodoulou (2009), *The Formation of Black Holes in General Relativity*
9. Geroch (1973), "Energy Extraction"
10. Geroch and Hartle (1982), "Distorted Black Holes"
11. Griffiths and Podolský (2009, chs. 8, 11), *Exact Space-Times in Einstein's General Relativity*
12. Heusler (1996), *Black Hole Uniqueness Theorems*

13. Joshi (2007, ch. 5), *Gravitational Collapse and Spacetime Singularities*
14. Misner, Thorne, and Wheeler (1973, chs. 23–25, 31–34), *Gravitation*
15. Poisson (2004, ch. 5, §§1, 3–4), *A Relativist's Toolkit: The Mathematics of Black-Hole Mechanics*
16. Rindler (2006, ch. 11), *Relativity: Special, General and Cosmological*
17. Schoen and Yau (1983), "The Existence of a Black Hole Due to Condensation of Matter"
18. Synge (1960, ch. VII), *Relativity: The General Theory*

Suggested Reading—Philosophy

1. Carter (2006), "Half Century of Black-Hole Theory: From Physicists' Purgatory to Mathematicians' Paradise"
2. Harper (2007), "Newton's Methodology and Mercury's Perihelion before and after Einstein"
3. Harper (2011, ch. 10), *Isaac Newton's Scientific Method: Turning Data Into Evidence about Gravity and Cosmology*
4. Israel (1987), "Dark Stars: The Evolution of an Idea"
5. Malament (2002), "A No-Go Theorem About Rotation in Relativity Theory"
6. Malament (2003), "On Relative Orbital Rotation in General Relativity"
7. Penrose (1980), "On Schwarzschild Causality—A Problem for 'Lorentz Covariant' General Relativity"

12 Week 12: The Laws of Black Hole Mechanics; Black Holes and Thermodynamics (Jun. 23)

the Four Laws of black-hole mechanics; the analogy with the thermodynamical Laws; the thermodynamical character of black holes

Required Reading

1. Bardeen, Carter, and Hawking (1973), "The Four Laws of Black Hole Mechanics"
2. Curiel (2014a), "Classical Black Holes Are Hot"
3. Israel (1986), "Third Law of Black Hole Mechanics: A Formulation of a Proof"
4. Wald (1984, ch. 12, §5), *General Relativity*
5. Wald and Gao (2001), "'Physical Process Version' of the First Law and the Generalized Second Law for Charged and Rotating Black Holes"
6. Wald (1994, ch. 6), *Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics*
7. 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 (1971), "Gravitational Radiation from Colliding Black Holes"
6. Hawking (1972), "Black Holes in General Relativity"
7. Hawking (1974), "Black Hole Explosions?"

8. Hawking (1975), "Particle Creation by Black Holes"
9. Hawking (1976a), "Black Holes and Thermodynamics"
10. Israel (1973), "Entropy and Black Hole Dynamics"
11. 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. Carter (1979), "The General Theory of the Mechanical, Electromagnetic and Thermodynamic Properties of Black Holes"
5. Flanagan, Marolf, and Wald (2000), "Proof of Classical Versions of the Bousso Entropy Bound and of the Generalized Second Law"
6. Hayward (1994), "General Laws of Black Hole Dynamics"
7. Hayward (2006), "Conservation Laws for Dynamical Black Holes"
8. Israel (1992), "Thermodynamics and Internal Dynamics of Black Holes: Some Recent Developments"
9. Israel (1998), "Gedanken Experiments in Black Hole Mechanics"
10. Jacobson (1999), "On the Nature of Black Hole Entropy"
11. Jacobson, Marolf, and Rovelli (2005), "Black Hole Entropy: Inside or Out?"
12. Jacobson and Parentani (2003), "Horizon Entropy"
13. Poisson (2004, ch. 5, §5), *A Relativist's Toolkit: The Mathematics of Black-Hole Mechanics*
14. Thorne, Price, and MacDonald (1986), *Black Holes: The Membrane Paradigm*
15. Unruh and Wald (1982), "Acceleration Radiation and the Generalized Second Law of Thermodynamics"
16. Wald (1993), "Black Hole Entropy Is the Noether Charge"
17. Wald (1997), "'Nernst Theorem' and Black Hole Thermodynamics"

Suggested Reading—Philosophy

1. Carter (2006), "Half Century of Black-Hole Theory: From Physicists' Purgatory to Mathematicians' Paradise"
2. Hawking and Penrose (1996, chs. 1, 3–4), *The Nature of Space and Time*
3. Sorkin (2005), "Ten Theses on Black Hole Entropy"
4. Wald (1999a), "Gravitation, Thermodynamics and Quantum Theory"

13 Week 13: Hawking Radiation (Jun. 30)

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. 't Hooft (1995), "Quantum Information and Information Loss in General Relativity"
15. Jacobson (2003), "Introduction to Quantum Fields in Curved Spacetime and the Hawking Effect"
16. Page (1980), "Is Black-Hole Evaporation Predictable?"
17. Page (1994), "Black Hole Information"
18. Unruh and Wald (1995), "On Evolution Laws Taking Pure States to Mixed States in Quantum Field Theory"
19. 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"

14 Week 14: Basic Cosmology; Cosmological Singularities and Thermodynamics (Jul. 07)

homogeneity and isotropy; derivation of the FLRW spacetimes and their properties; dark energy and the cosmological constant; 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. Malament (2012, §2.11), *Topics in the Foundations of General Relativity and Newtonian Gravitational Theory*
4. Newman (1993), "On the Structure of Conformal Singularities in Classical General Relativity"

5. Penrose (1979), "Singularities and Time-Asymmetry"
6. Wald (1984, ch. 5), *General Relativity*
7. Wallace (2010), "Gravity, Entropy, and Cosmology: In Search of Clarity"

Suggested Reading—Physics

1. Anderson (1967, ch. 14), *Principles of Relativity Physics*
2. Barrow (2004a), "More General Sudden Singularities"
3. Bekenstein (1975), "Nonsingular General-Relativistic Cosmologies"
4. Caldwell (2002), "A Phantom Menace? Cosmological Consequences of a Dark Energy Component with Super-Negative Equation of State"
5. Caldwell, Kamionkowski, and Weinberg (2003), "Phantom Energy: Dark Energy with $w < -1$ Causes a Cosmic Doomsday"
6. Cattoën and Visser (2008), "Cosmodynamics: Energy Conditions, Hubble Bounds, Density Bounds, Time and Distance Bounds"
7. Cattoën and Visser (2005), "Necessary and Sufficient Conditions for Big Bangs, Bounces, Crunches, Rips, Sudden Singularities and Extremality Events"
8. Cattoën and Visser (2007), "Cosmological Milestones and Energy Conditions"
9. Choquet-Bruhat (2009, ch. V), *General Relativity and the Einstein Equations*
10. Chimento and Lazkoz (2004), "On Big Rip Singularities"
11. Cotsakis and Klaoudatou (2007), "Cosmological Singularities and Bel-Robinson Energy"
12. Dabrowski, Stachowiak, and Szydłowski (2003), "Phantom Cosmologies"
13. Dabrowski and Denkiewicz (2009), "Barotropic Index w-Singularities in Cosmology"
14. Ellis, Maartens, and MacCallum (2012, chs. 5–9, 13–14, 17–19), *Relativistic Cosmology*
15. L. and Lazkoz (2006), "Classification of Cosmological Milestones"
16. Goode and Wainwright (1985), "Isotropic Singularities in Cosmological Models"
17. Griffiths and Podolský (2009, chs. 4–6; ch. 22, §§1–2, 7–8), *Exact Space-Times in Einstein's General Relativity*
18. Hawking and Ellis (1973, ch. 5, §§2—4, 7), *The Large Scale Structure of Space-Time*
19. Joshi (1993, ch. 8), *Global Aspects in Gravitation and Cosmology*
20. Krasiński (2006, chs. 1–3, 6), *Inhomogeneous Cosmological Models*
21. Malament (2012, ch. 3, §1), *Topics in the Foundations of General Relativity and Newtonian Gravitational Theory*
22. Misner, Thorne, and Wheeler (1973, chs. 27–30), *Gravitation*
23. Ellis and Sciama (1972), "Global and Non-Global Problems in Cosmology"
24. Shepley and Ryan (1978), *Homogeneous Cosmological Models*
25. Stephani, Kramer, MacCallum, Hoenselaers, and Herlt (2009, chs. 13–14, 23), *Exact Solutions of Einstein's Field Equations*
26. Tod (2002), "Isotropic Cosmological Singularities"
27. Visser (1997a), "Energy Conditions in the Epoch of Galaxy Formation"
28. Visser (1997b), "General Relativistic Energy Conditions: The Hubble Expansion in the Epoch of Galaxy Formation"
29. Visser (2005), "Cosmography: Cosmology without the Einstein Equation"
30. Weinberg (1972, ch. 14, §§1–6), *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*
31. 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"

15 PAPER DUE (Sep. 19)

References

Anderson, J. (1962). Absolute change in general relativity. In *Recent Developments in General Relativity*, pp. 121–126. Oxford: Pergamon Press. Volume commemorating the 60th birthday of Leopold Infeld, with no editors mentioned by name.

Anderson, J. (1967). *Principles of Relativity Physics*. New York: Academic Press.

Ansoldi, S. (2007). Spherical black holes with regular center: A review of existing models including a recent realization with Gaussian sources. In L. Fatibene, M. Francaviglia, R. Giambò, and G. Magli (Eds.), *Dynamics and Thermodynamics of Blackholes and Naked Singularities*. Proceedings of a conference, 10–12 May, Department of Mathematics of the Politecnico, Milan. Conference version available at `http://www1.mate.polimi.it/bh2/Ansoldi.pdf`. Preprint available at arXiv:0802.0330 [gr-qc].

Ashtekar, A. (2003). How black holes grow. arXiv:gr-qc/0306115v1. The text of a plenary talk given at the conference "Mathematical Physics, General Relativity and Cosmology", Mexico City, September, 2002, in honor of Professor Jerzy Plebański.

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.

Bardeen, J., B. Carter, and S. Hawking (1973). The four laws of black hole mechanics. *Communications in Mathematical Physics 31*(2), 161–170. doi:10.1007/BF01645742.

Barrow, J. (2004a). More general sudden singularities. *Classical and Quantum Gravity 21*(11), 5619–5622. doi:10.1088/0264-9381/21/23/020.

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

Bekenstein, J. (1972a). Black holes and the second law. *Lettere al Nuovo Cimento 4*, 737–740.

Bekenstein, J. (1972b). Nonexistence of baryon number for static black holes. *Physical Review 5*(6), 1239–1246. doi:10.1103/PhysRevD.5.1239.

Bekenstein, J. (1973a). Black holes and entropy. *Physical Review D 7*, 2333–2346. doi:10.1103/PhysRevD.7.2333.

Bekenstein, J. (1973b). Extraction of energy and charge from a black hole. *Physical Review D 7*(4), 949–953. doi:10.1103/PhysRevD.7.949.

Bekenstein, J. (1974). Generalized second law of thermodynamics in black-hole physics. *Physical Review D 9*, 3292–3300. doi:10.1103/PhysRevD.9.3292.

Bekenstein, J. (1975). Nonsingular general-relativistic cosmologies. *Physical Review D 11*(8), 2072–2075. doi:10.1103/PhysRevD.11.2072.

Bekenstein, J. (1983). Entropy bounds and the second law for black holes. *Physical Review D 27*, 2262–2270. doi:10.1103/PhysRevD.27.2262.

Bekenstein, J. (1994). Do we understand black hole entropy? In R. J. Ruffini, R. and G. MacKeiser (Eds.), *Proceedings of the 7th Marcel Grossmann Meeting on General Relativity*, pp. 39–58. Singapore: World Scientific Press. Preprint available at arXiv:gr-qc/9409015v2.

Bekenstein, J. (1999). Non-Archimedean character of quantum buoyancy and the Generalized Second Law of thermodynamics. *Physical Review D 60*, 124010. Preprint available at arXiv:gr-qc/9906058v1.

Bekenstein, J. (2000). The limits of information. arXiv:gr-qc/0009019v2.

Belot, G. (1996). Why general relativity *does* need an interpretation. *Philosophy of Science 63*(Proceedings), S80–S88.

Belot, G. (2005). Dust, time and symmetry. *British Journal for the Philosophy of Science 56*(2), 255–291.

Belot, G., J. Earman, and L. Ruetsche (1999). The hawking information loss paradox: The anatomy of controversy. *British Journal for the Philosophy of Science 50*(2), 189–229.

Bergmann, P. (1977). Geometry and observables. See Earman and Stachel (1977), pp. 275–280.

Bondi, H. (1955). Fact and inference in theory and in observation. *Vistas in Astronomy 1*, 155–162. doi:10.1016/0083-6656(55)90020-9. Reprinted in A. Beer (ed.), *Vistas in Astronomy*, volume 1, Pergamon Press, Oxford, 1960, a *festschrift* for F. J. M. Stratton, as a special Supplement No. 3 to the *Journal of Atmospheric and Terrestrial Physics*.

Borde, A. (1987). Geodesic focusing, energy conditions and singularities. *Classical and Quantum Gravity 4*(2), 343–356. doi:10.1088/0264-9381/4/2/015.

Bosshard, B. (1976). On the *b*-boundary of the closed Friedmann model. *Communications in Mathematical Physics 46*, 263–268.

Bosshard, B. (1979). On *b*-boundaries of special space-time models. *General Relativity and Gravitation 10*, 963–966.

Brown, H. (2005). *Physical Relativity: Space-time Structure from a Dynamical Perspective*. Oxford: Oxford University Press.

Caldwell, R. (2002, 03 October). A phantom menace? Cosmological consequences of a dark energy component with super-negative equation of state. *Physics Letters B 545*, 23–29. doi:10.1016/S0370-2693(02)02589-3. Preprint available at arXiv:astro-ph/9908168v2.

Caldwell, R., M. Kamionkowski, and N. Weinberg (2003). Phantom energy: Dark energy with $w < -1$ causes a cosmic doomsday. *Physical Review Letters 91*, 071301. doi:10.1103/PhysRevLett.91.071301. Preprint available at arXiv:astro-ph/0302506.

Carter, B. (1968). Global structure of the Kerr family of gravitational fields. *Physical Review 174*, 1559–1571.

Carter, B. (1969). Killing horizons and orthogonally transitive groups in space-time. *Journal of Mathematical Physics 10*, 70–81. doi:10.1063/1.1664763.

Carter, B. (1971a). Axisymmetric black hole has only two degrees of freedom. *Physical Review Letters 26*, 331–333. doi:10.1103/PhysRevLett.26.331.

Carter, B. (1971b). Causal structure in space-time. *General Relativity and Gravitation 1*(4), 349–391. doi:10.1007/BF00759217.

Carter, B. (1973). Black hole equilibrium states. See DeWitt and DeWitt (1973), pp. 56–214.

Carter, B. (1979). The general theory of the mechanical, electromagnetic and thermodynamic properties of black holes. See Hawking and Israel (1979), Chapter 6, pp. 294–369.

Carter, B. (1999). The black hole equilibrium problem. In B. Iyer and B. Bhawal (Eds.), *Black Holes, Gravitational Radiation and the Universe*, pp. 1–16. Dordrecht: Kluwer Academic Publishers.

Carter, B. (2006). Half century of black-hole theory: From physicists' purgatory to mathematicians' paradise. In L. Mornas and J. D. Alonso (Eds.), *A Century of Relativity Physics*. American Institute of Physics. Proceedings of the XXVIII$^{\text{th}}$ Spanish Relativity Meeting.

Cattoën, C. and M. Visser (2005). Necessary and sufficient conditions for big bangs, bounces, crunches, rips, sudden singularities and extremality events. *Classical and Quantum Gravity 22*, 4913–4930. doi:10.1088/0264-9381/22/23/001.

Cattoën, C. and M. Visser (2007). Cosmological milestones and energy conditions. *Journal of Physics Conference Series 68*, 012011. Paper given at 12th Conference on Recent Developments in Gravity. doi:10.1088/1742-6596/68/1/012011. Preprint available at arXiv:gr-qc/0609064.

Cattoën, C. and M. Visser (2008). Cosmodynamics: Energy conditions, Hubble bounds, density bounds, time and distance bounds. *Classical and Quantum Gravity 25*(16), 165013. doi:10.1088/0264-9381/25/16/165013. Preprint available at arXiv:0712.1619 [gr-qc].

Chandrasekhar, S. (1983). *The Mathematical Theory of Black Holes*. Oxford: Oxford University Press.

Chimento, L. and R. Lazkoz (2004, 30 October). On big rip singularities. *Modern Physics Letters A 19*(33), 2479–2485. doi:10.1142/S0217732304015646. Preprint available at arXiv:gr-qc/0405020.

Choquet-Bruhat, Y. (2009). *General Relativity and the Einstein Equations*. Oxford Mathematical Monographs. Oxford: Oxford University Press.

Christodoulou, D. (1970). Reversible and irreversible transformations in general relativity. *Physical Review Letters 25*(22), 1596–1597. doi:10.1103/PhysRevLett.25.1596.

Christodoulou, D. (2009). *The Formation of Black Holes in General Relativity*. EMS Monographs in Mathematics. Zürich: European Mathematical Society.

Clarke, C. (1973). Local extensions in singular space-times. *Communications in Mathematical Physics 32*, 205–214.

Clarke, C. (1975a). The classification of singularities. *General Relativity and Gravitation 6*, 35–40.

Clarke, C. (1975b). Singularities in globally hyperbolic space-times. *Communications in Mathematical Physics 41*, 65–78.

Clarke, C. (1976). Space-time singularities. *Communications in Mathematical Physics 49*, 17–23.

Clarke, C. (1979a). Boundary definitions. *General Relativity and Gravitation 10*, 977–980.

Clarke, C. (1979b). The nature of singularities. *General Relativity and Gravitation 10*, 999–1002.

Clarke, C. (1993). *The Analysis of Space-Time Singularities*. Number 1 in Cambridge Lecture Notes in Physics. Cambridge: Cambridge University Press.

Clarke, C. and A. Królak (1985). Conditions for the occurrence of strong curvature singularities. *Journal of Geometry and Physics 2*, 127–143.

Clarke, C. and B. Schmidt (1977). Singularities: The state of the art. *General Relativity and Gravitation 8*, 129–137.

Clifton, T., G. Ellis, and R. Tavakol (2013). A gravitational entropy proposal. *Classical and Quantum Gravity 30*(12), 125009. doi:10.1088/0264-9381/30/12/125009. Preprint available at arXiv:1303.5612 [gr-qc].

Cotsakis, S. and I. Klaoudatou (2007). Cosmological singularities and Bel-Robinson energy. *Journal of Geometry and Physics 57*(4), 1303–1312. doi:10.1016/j.geomphys.2006.10.007. Preprint available at arXiv:gr-qc/0604029v2.

Curiel, E. (1999). The analysis of singular spacetimes. *Philosophy of Science 66*(Proceedings), 119–145. A more recent version, with corrections and emendations, is available at `http://strangebeautiful.com/phil-phys.html`.

Curiel, E. (2000). The constraints general relativity places on physicalist accounts of causality. *Theoria 15*(1), 33–58.

Curiel, E. (2009). General relativity needs no interpretation. *Philosophy of Science 76*(1), 44–72.

Curiel, E. (2013). On tensorial concomitants and the non-existence of a gravitational stress-energy tensor. This paper has been submitted for review at *Journal of Mathematical Physics*.

Curiel, E. (2014a). Classical black holes are hot. Unpublished manuscript.

Curiel, E. (2014b). Energy conditions and cosmology. Preparing to submit to *Studies in History and Philosophy of Modern Physics*.

Curiel, E. (2014c). On the existence of spacetime structure. Unpublished manuscript.

Curiel, E. (2014d). A primer on energy conditions. Preparing to submit to *British Journal of Philosophy of Science*.

Dabrowski, M. and T. Denkiewicz (2009). Barotropic index w-singularities in cosmology. *Physical Review D 79*(6), 063521. doi:10.1103/PhysRevD.79.063521.

Dabrowski, M., T. Stachowiak, and M. Szydłowski (2003). Phantom cosmologies. *Physical Review D 68*(10), 103519. doi:10.1103/PhysRevD.68.103519.

Davies, P. and J. Taylor (1974). Do black holes really explode? *Nature 250*, 37–38.

DeWitt, B. and C. DeWitt (Eds.) (1973). *Black Holes*. New York: Gordon and Breach.

DeWitt, C. and J. Wheeler (Eds.) (1968). *Battelle Rencontres*. New York: W. A. Benjamin.

Dicke, R. (1962). Mach's principle and equivalence. In C. Møller (Ed.), *Evidence for Gravitational Theories*, Number XX in International School of Physics «Enrico Fermi», pp. 1–49. New York: Academic Press.

Dicke, R. and P. Peebles (1979). The big bang cosmology—enigmas and nostrums. See Hawking and Israel (1979), Chapter 9, pp. 504–517.

DiSalle, R. (2006). *Understanding Space-Time: The Philosophical Development of Physics from Newton to Einstein*. Cambridge: Cambridge University Press.

Earman, J., C. G. and J. Stachel (Eds.) (1977). *Foundations of Space-Time Theories*, Volume VII of *Minnesota Studies in Philosophy of Science*. Minneapolis: University of Minnesota Press.

Earman, J. (1989). *World Enough and Space-Time: Absolute versus Relational Theories of Space and Time*. Cambridge, MA: MIT Press.

Earman, J. (1995). *Bangs, Crunches, Whimpers and Shrieks: Singularities and Acausalities in Relativistic Spacetimes*. Oxford: Oxford University Press.

Earman, J. and J. Eisenstaedt (1999). Einstein and singularities. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics 30*(2), 185–235.

Earman, J. and J. Norton (1987). What price spacetime substantivalism? The hole story. *Philosophy of Science 38*, 515–525.

Earman, J., C. Smeenk, and C. Wüthrich (2009). Do the laws of physics forbid the operation of time machines? *Synthese 169*(1), 91–124.

Eddington, A. (1920). *Space, Time & Gravitation: An Outline of the General Theory of Relativity*. Cambridge: Cambridge University Press. A 1987 reprint of the 1920 original, part of the Cambridge Science Classics series.

Eddington, A. (1923). *Mathematical Theory of Relativity* (second ed.). Cambridge: Cambridge University Press.

Ehlers, J. (Ed.) (1967). *Relativity Theory and Astrophysics: 1. Relativity and Cosmology*, Volume 8 of *Lectures in Applied Mathematics*. Providence, RI: American Mathematical Society. Proceedings of the Fourth Summer Seminar on Applied Mathematics, Cornell University, Jul. 26–Aug. 20, 1965.

Ehlers, J. (1987). Folklore in relativity and what is really known. In M. MacCallum (Ed.), *General Relativity and Gravitation*, pp. 61–71. Cambridge: Cambridge University Press. Proceedings of the 11th International Conference on General Relativity and Gravitation, Stockholm, July 6–12, 1986.

Ehlers, J., F. Pirani, and A. Schild (1972). The geometry of free fall and light propagation. See O'Raifeartaigh (1972), Chapter 4, pp. 63–84.

Einstein, A. (1915). On the general theory of relativity. In *The Collected Papers of Albert Einstein (The Berlin Years: Writings, 1914–1917)*, Volume 6, pp. 98–108. Princeton: Princeton University Press. Published originally as "Zur allgemeinen Relativitätstheorie", *Königlich Preußische Akademie der Wissenschaften* (Berlin). Sitzungsberichte (1915), p. 774.

Einstein, A. (1984). *The Meaning of Relativity* (fifth ed.). Princeton: Princeton University Press. Trans. E. Adams, E. Straus and S. Bargmann. First edition published in 1922.

Ellis, G. (2007). Issues in the philosophy of cosmology. In J. Butterfield and J. Earman (Eds.), *Handbook of Philosophy of Physics, Part B*, pp. 1183–1286. Dordrecht: North Holland. Preprint available at arXiv:astro-ph/0602280v2.

Ellis, G., R. Maartens, and M. MacCallum (2012). *Relativistic Cosmology*. Cambridge: Cambridge University Press.

Ellis, G. and B. Schmidt (1977). Singular space-times. *General Relativity and Gravitation 8*(11), 915–953. doi:10.1007/BF00759240.

Ellis, G. and B. Schmidt (1979). Classification of singular space-times. *General Relativity and Gravitation 10*, 989–997.

Ellis, G. and D. Sciama (1972). Global and non-global problems in cosmology. See O'Raifeartaigh (1972), Chapter 3, pp. 35–62.

Fewster, C. and G. Galloway (2011). Singularity theorems from weakened energy conditions. *Classical and Quantum Gravity 28*(12), 125009. doi:10.1088/0264-9381/28/12/125009. Preprint available at arXiv:1012.6038 [gr-qc].

Flanagan, E., D. Marolf, and R. Wald (2000). Proof of classical versions of the Bousso entropy bound and of the Generalized Second Law. *Physical Review D 62*(8), 084035. doi:10.1103/PhysRevD.62.084035. Preprint available at arXiv:hep-th/9908070v4.

Fredenhagen, K. and R. Haag (1990). On the derivation of the Hawking radiation associated with the formation of a black hole. *Communications in Mathematical Physics 127*, 273–284.

Friedman, M. (1983). *Foundations of Space-Time Theories: Relativistic Physics and Philosophy of Science*. Princeton: Princeton University Press.

Galloway, G. and A. Horta (1996, May). Regularity of Lorentzian Busemann functions. *Transactions of the American Mathematical Society 348*(5), 2063–2084.

Gannon, D. (1975). Singularities in nonsimply connected space-times. *Journal of Mathematical Physics 16*(12), 2364–2367. doi:10.1063/1.522498.

Garcia-Parrado, A. and J. Senovilla (2005). Causal structures and causal boundaries. *Classical and Quantum Gravity 22*(9), R1–R84. doi:10.1088/0264-9381/22/9/R01. Preprint available at arXiv:gr-qc/0501069.

Gauss, C. F. (1979). General investigations of curved surfaces. See Spivak (1979b), Chapter 3A, pp. 57–111. A translation of the original "Disquisitiones Generales circa Superficies Curvas" of 1827.

Geroch, R. (1966). Singularities in closed universes. *Physical Review Letters 17*, 445–447. doi:10.1103/PhysRevLett.17.445.

Geroch, R. (1968a). Local characterization of singularities in general relativity. *Journal of Mathematical Physics 9*, 450–465.

Geroch, R. (1968b). The structure of singularities. SeeDeWitt and Wheeler (1968), pp. 236–241.

Geroch, R. (1968c). What is a singularity in general relativity? *Annals of Physics 48*, 526–540.

Geroch, R. (1970a). Domain of dependence. *Journal of Mathematical Physics 11*(2), 437–449.

Geroch, R. (1970b). Singularities. In M. Carmeli, S. Fickler, and L. Witten (Eds.), *Relativity*, pp. 259–291. New York: Plenum Press.

Geroch, R. (1971a). General relativity in the large. *General Relativity and Gravitation 2*(1), 61–74.

Geroch, R. (1971b). Space-time structure from a global viewpoint. In R. Sachs (Ed.), *General Relativity and Cosmology*, Number XLVII in Proceedings of the International School of Physics

≪Enrico Fermi≫, pp. 71–103. New York: Academic Press. Varenna on Lake Como, Villa Monastero, 30th June–12th July, 1969.

Geroch, R. (1972). Structure of the gravitational field at spatial infinity. *Journal of Mathematical Physics 13*, 956–968.

Geroch, R. (1973, December). Energy extraction. *Annals of the New York Academy of Sciences 224*, 108–117. Proceedings of the Sixth Texas Symposium on Relativistic Astrophysics. doi:10.1111/j.1749-6632.1973.tb41445.x.

Geroch, R. (1977a). Asymptotic structure of space-time. In F. Esposito and L. Witten (Eds.), *Asymptotic Structure of Space-Time*, pp. 1–106. New York: Plenum Press. Proceedings of a symposium held at the University of Cincinatti, Ohio, June 14–18, 1976.

Geroch, R. (1977b). Prediction in general relativity. See Earman and Stachel (1977), pp. 81–93.

Geroch, R. (1981). *General Relativity from A to B*. Chicago: University of Chicago Press.

Geroch, R. (1983). The local nonsingularity theorem. *Journal of Mathematical Physics 24*(7), 1851–1858.

Geroch, R., L. Can-bin, and R. Wald (1982). Singular boundaries of space-times. *Journal of Mathematical Physics 23*, 432–435.

Geroch, R. and J. Hartle (1982). Distorted black holes. *Journal of Mathematical Physics 23*, 680.

Geroch, R. and G. Horowitz (1979). Global structure of spacetimes. See Hawking and Israel (1979), Chapter 5, pp. 212–293.

Geroch, R., E. Kronheimer, and R. Penrose (1972). Ideal points in space-time. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences 327*, 545–567.

Glymour, C. (1977). Indistinguishable space-times and the fundamental group. See Earman and Stachel (1977), pp. 50–60.

Goode, S. and J. Wainwright (1985). Isotropic singularities in cosmological models. *Classical and Quantum Gravity 2*, 99–115.

Griffiths, J. and J. Podolský (2009). *Exact Space-Times in Einstein's General Relativity*. Cambridge: Cambridge University Press.

Harper, W. (2007). Newton's methodology and Mercury's perihelion before and after Einstein. *Philosophy of Science 74*(5), 932–942.

Harper, W. (2011). *Isaac Newton's Scientific Method: Turning Data Into Evidence about Gravity and Cosmology*. Oxford: Oxford University Press.

Hartle, J. (1994). Spacetime information. *Physical Review D 51*, 1800–1817. Preprint available at arXiv:gr-qc/9409005v1.

Hartle, J. (1998). Generalized quantum theory in evaporating black hole spacetimes. See Wald (1998), pp. 195–219. Preprint available at arXiv:gr-qc/9808070v1.

Hartle, J. and S. Hawking (1976). Path-integral derivation of black hole radiance. *Physical Review D 13*, 2188–2203.

Hawking, S. (1965). Occurrence of singularities in open universes. *Physical Review Letters 15*, 689–690. doi:10.1103/PhysRevLett.15.689.

Hawking, S. (1966a). The occurrence of singularities in cosmology. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences 294*, 511–521. doi:10.1098/rspa.1966.0221.

Hawking, S. (1966b). The occurrence of singularities in cosmology. II. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences 295*, 490–493. doi:10.1098/rspa.1966.0255.

Hawking, S. (1966c). Singularities in the universe. *Physical Review Letters 17*, 444–445. doi:10.1103/PhysRevLett.17.444.

Hawking, S. (1967). The occurrence of singularities in cosmology. III: causality and singularities. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences 300*, 187–210. doi:10.1098/rspa.1967.0164.

Hawking, S. (1971). Gravitational radiation from colliding black holes. *Physical Review Letters 26*(21), 1344–1346. doi:10.1103/PhysRevLett.26.1344.

Hawking, S. (1972). Black holes in general relativity. *Communications in Mathematical Physics 25*(2), 152–166. doi:10.1007/BF01877517.

Hawking, S. (1973). The event horizon. See DeWitt and DeWitt (1973), pp. 1–55.

Hawking, S. (1974, 01 March). Black hole explosions? *Nature 248*, 30–31. doi:10.1038/248030a0.

Hawking, S. (1975). Particle creation by black holes. *Communications in Mathematical Physics 43*, 199–220. doi:10.1007/BF02345020.

Hawking, S. (1976a, January). Black holes and thermodynamics. *Physical Review D 13*(2), 191–197. doi:10.1103/PhysRevD.13.191.

Hawking, S. (1976b). Breakdown of predictability in gravitational collapse. *Physical Review D 14*, 2460–2473.

Hawking, S. (1986). Chronology protection conjecture. *Physical Review D 46*(2), 603–611. doi:10.1103/PhysRevD.46.603.

Hawking, S. (1998). Loss of information in black holes. In S. Huggett, S. T. L. Mason, K. Tod, and N. Woodhouse (Eds.), *The Geometric Universe: Science, Geometry, and the Work of Roger Penrose*, pp. 123–133. Oxford: Oxford University Press.

Hawking, S. (2005). Information loss in black holes. *Physical Review D 72*, 084013. Preprint available at arXiv:hep-th/0507171v2.

Hawking, S. and G. Ellis (1965, 15 July). Singularities in homogeneous world models. *Physics Letters 17*(3), 246–247. doi:10.1016/0031-9163(65)90510-X.

Hawking, S. and G. Ellis (1969). The cosmic black body radiation and the existence of singularities in our universe. *Astrophysical Journal 152*, 25–36. doi:10.1086/149520.

Hawking, S. and G. Ellis (1973). *The Large Scale Structure of Space-Time*. Cambridge: Cambridge University Press.

Hawking, S. and W. Israel (Eds.) (1979). *General Relativity: An Einstein Centenary Survey*. Cambridge University Press.

Hawking, S. and R. Penrose (1970). The singularities of gravitational collapse and cosmology. *Philosophical Transactions of the Royal Society (London) A 314*, 529–548. doi:10.1098/rspa.1970.0021.

Hawking, S. and R. Penrose (1996). *The Nature of Space and Time*. Isaac Newton Institute Series of Lectures. Princeton: Princeton University Press.

Hayward, S. (1994). General laws of black hole dynamics. *Physical Review D 49*(12), 6467–6474. doi:10.1103/PhysRevD.49.6467. Preprint available at arXiv:gr-qc/9303006v3.

Hayward, S. (2005). The dis-information problem for black holes (conference version). arXiv:gr-qc/0504037v1.

Hayward, S. (2006). Conservation laws for dynamical black holes. arXiv:gr-qc/0607081v2.

Helmholtz, H. (1870). Über den Ursprung und die Bedeutung der geometrischen Axiome. In *Populäre Wissenschaftliche Vorträge von H. Helmholtz*, Volume 3, pp. 23–51. Braunschweig. A lecture delivered in the Docentverein of Heidelberg, 1870. English translation by Howard Stein (unpublished), "On the Origin and Significance of the Geometrical Axioms", available online at `http://strangebeautiful.com/other-minds.html#helmholtz.`

Heusler, M. (1996). *Black Hole Uniqueness Theorems*. Number 6 in Cambridge Lecture Notes in Physics. Cambridge: Cambridge University Press.

Hoefer, C. (2000). Energy conservation in GTR. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics 31*(2), 187–199.

Howard, D. and J. Stachel (Eds.) (1989). *Einstein and the History of General Relativity*, Volume 1 of *Einstein Studies*. Berlin: Birkhaüser. The proceedings of the 1986 Osgood Hill Conference, North Andover, MA, 8–11 May 1986.

Israel, W. (1967). Event horizons in static vacuum space-times. *Physical Review 164*(5), 1776–1779. doi:10.1103/PhysRev.164.1776.

Israel, W. (1973). Entropy and black hole dynamics. *Lettere al Nuovo Cimento 2*, 267–269.

Israel, W. (1986). Third law of black hole mechanics: A formulation of a proof. *Physical Review Letters 57*(4), 397–399. doi:10.1103/PhysRevLett.57.397.

Israel, W. (1987). Dark stars: The evolution of an idea. In S. Hawking and W. Israel (Eds.), *300 Years of Gravitation*, pp. 199–276. Cambridge University Press.

Israel, W. (1992). Thermodynamics and internal dynamics of black holes: Some recent developments. In V. de Sabbata and Z. Zhang (Eds.), *Black Hole Physics*, pp. 147–183. Dordrecht: Kluwer Academic Publishers.

Israel, W. (1998). Gedanken experiments in black hole mechanics. In F. Hehl, C. Kiefer, and R. Metzler (Eds.), *Black Holes: Theory and Observation*, pp. 339–363. Berlin: Springer-Verlag. Proceedings of the 179th W. E. Heraeus Seminar, Bad Honnef, Germany, 18–22 Aug 1997.

Jacobson, T. (1999). On the nature of black hole entropy. In C. Burgess and R. Myers (Eds.), *General Relativity and Relativistic Astrophysics*, pp. 85–97. College Park, MD: American Institute of Physics. Preprint available at arXiv:gr-qc/9908031v2.

Jacobson, T. (2003). Introduction to quantum fields in curved spacetime and the Hawking effect. arXiv:gr-qc/0308048v3.

Jacobson, T., D. Marolf, and C. Rovelli (2005). Black hole entropy: Inside or out? arXiv:hep-th/0501103v1.

Jacobson, T. and R. Parentani (2003, February). Horizon entropy. *Foundations of Physics 33*(2), 323–348. doi:10.1023/A:1023785123428. Preprint available at arXiv:gr-qc/0302099v1.

Jammer, M. (1961). *Concepts of Mass in Classical and Modern Physics*. Mineola, NY: Dover Publications, Inc. A 1997 reprint of the original 1961 edition published by Harvard University Press.

Johnson, R. (1977). The bundle boundary in some special cases. *Journal of Mathematical Physics 18*, 898–902.

Johnson, R. (1979). The bundle boundary for the Schwarzschild and Friedmann solutions. *General Relativity and Gravitation 10*, 967–968.

Joshi, P. (1993). *Global Aspects in Gravitation and Cosmology*. Number 87 in International Series of Monographs on Physics. Oxford: Oxford University Press.

Joshi, P. (2003). Cosmic censorship: A current perspective. *Modern Physics Letters A 17*(15), 1067–1079. doi:10.1142/S0217732302007570. Preprint available at arXiv:gr-qc/0206087.

Joshi, P. (2007). *Gravitational Collapse and Spacetime Singularities*. Cambridge Monographs on Mathematical Physics. Cambridge: Cambridge University Press.

Kerr, R. (1963). Gravitational field of a spinning mass as an example of algebraically special metrics. *Physical Review Letters 11*, 237–238.

King, A. (1974). New types of singularity in general relativity: The general cylindrically symmetric stationary dust solution. *Communications in Mathematical Physics 38*, 157–171.

Konkowski, D. and T. Helliwell (1992). Singularities in colliding plane-wave spacetimes. In G. Kunstatter (Ed.), *General Relativity and Relativistic Astrophysics*, pp. 115–119. Singapore: World Scientific.

Krasiński, A. (2006). *Inhomogeneous Cosmological Models*. Cambridge: Cambridge University Press.

Kronheimer, E. and R. Penrose (1967). On the structure of causal spaces. *Proceedings of the Cambridge Philosophical Society 63*, 481–501.

L., F.-J. and R. Lazkoz (2006). Classification of cosmological milestones. *Physical Review D 74*, 064030. doi:10.1103/PhysRevD.74.064030. Preprint available at arXiv:gr-qc/0607073.

Lichnerowicz, A. and A. Tonnelat (Eds.) (1962). *Les Théories Relativistes de la Gravitation*, Number 91 in Colloques Internationaux, Paris. Centre National de la Recherche Scientifique. Proceedings of a conference held at Royaumont in June, 1959.

Lorentz, H., A. Einstein, H. Minkowski, and H. Weyl (1952). *The Principle of Relativity*. New York: Dover Press, 1952. W. Perrett and G. Jeffery, translators.

Malament, D. (1977a). The class of continuous timelike curves determines the topology of spacetime. *Journal of Mathematical Physics 18*(7), 1399–1404. doi:10.1063/1.523436.

Malament, D. (1977b). Observationally indistinguishable spacetimes: Comments on Glymour's paper. See Earman and Stachel (1977), pp. 61–80.

Malament, D. (2002). A no-go theorem about rotation in relativity theory. In D. Malament (Ed.), *Reading Natural Philosophy: Essays in the History and Philosophy of Science and Mathematics*. Chicago: Open Court Press. Essays presented to Howard Stein in honor of his 70th birthday, delivered at a *festchrift* in Stein's honor at the University of Chicago, May, 1999.

Malament, D. (2003). On relative orbital rotation in general relativity. In A. Ashtekar (Ed.), *Revisiting the Foundations of Relativistic Physics: Festschrift for John Stachel*. Dordrecht: Kluwer.

Malament, D. (2012). *Topics in the Foundations of General Relativity and Newtonian Gravitational Theory*. Chicago: University of Chicago Press. Uncorrected final proofs for the book are available for download at http://strangebeautiful.com/other-texts/malament-founds-gr-ngt.pdf.

Manchak, J. (2008). Is prediction possible in general relativity? *Foundations of Physics 38*, 317–321.

Manchak, J. (2009a). Can we know the global structure of spacetime? *Studies in History and Philosophy of Modern Physics 40*, 53–56.

Manchak, J. (2009b). Is spacetime hole-free? *General Relativity and Gravitation 41*, 1639–1643.

Manchak, J. (2009c). On the existence of 'time machines' in general relativity. *Philosophy of Science 76*, 1020–1026.

Manchak, J. (2011a). No no-go: A remark on time machines. *Studies in History and Philosophy of Modern Physics 42*, 74–76.

Manchak, J. (2011b). What is a physically reasonable spacetime? *Philosophy of Science 78*, 410–420.

Manchak, J. (2012). On the relationship between spacetime singularities, holes, and extensions. Unpublished manuscript, available online (http://faculty.washington.edu/manchak/manchak.ecompleteness.pdf).

Misner, C. (1967). Taub-NUT space as a counterexample to almost anything. See Ehlers (1967), pp. 160–169. Proceedings of the Fourth Summer Seminar on Applied Mathematics, Cornell University, Jul. 26–Aug. 20, 1965.

Misner, C., K. Thorne, and J. Wheeler (1973). *Gravitation*. San Francisco: Freeman Press.

Møller, C. (1962). The energy-momentum complex in general relativity and related problems. See Lichnerowicz and Tonnelat (1962), pp. 15–29. Proceedings of a conference held at Royaumont in June, 1959.

Müller zum Hagen, H., D. Robinson, and H. Seifert (1973). Black holes in static vacuum spacetimes. *General Relativity and Gravitation 4*(1), 53–78. doi:10.1007/BF00769760.

Munitz, M. (1962). The logic of cosmology. *British Journal for the Philosophy of Science 13*, 34–50.

Newman, R. (1993). On the structure of conformal singularities in classical general relativity. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences 443*, 473–492.

Norton, J. (1985). What was Einstein's principle of equivalence? *Studies in History and Philosophy of Science 16*, 203–246.

Norton, J. (1989). How Einstein found his field equations, 1912–1915. See Howard and Stachel (1989), pp. 101–159. The proceedings of the 1986 Osgood Hill Conference, North Andover, MA, 8–11 May 1986.

Norton, J. (1993). General covariance and the foundations of general relativity: Eight decades of dispute. *Reports on Progress in Physics 56*, 791–858.

O'Raifeartaigh, L. (Ed.) (1972). *General Relativity: Papers in Honour of J. L. Synge*. Oxford: Clarendon Press.

Page, D. (1980). Is black-hole evaporation predictable? *Physical Review Letters 44*, 301–304.

Page, D. (1994). Black hole information. In R. Mann and R. McLenaghan (Eds.), *Proceedings of the 5th Canadian Conference on General Relativity and Relativistic Astrophysics*, Singapore, pp. 1–41. World Scientific Press. Lecture delivered at the conference held at the University of Waterloo, 13–15 May, 1993. Preprint available at arXiv:hep-th/9305040v5.

Page, D. (2005). Hawking radiation and black hole thermodynamics. *New Journal of Physics 7*, 203. doi:10.1088/1367-2630/7/1/203. Preprint available at arXiv:hep-th/0409024.

Penrose, R. (1965). Gravitational collapse and space-time singularities. *Physical Review Letters 14*(3), 57–59. doi:10.1103/PhysRevLett.14.57.

Penrose, R. (1967). Conserved quantities and conformal structure in general relativity. See Ehlers (1967), pp. 147–159. Proceedings of the Fourth Summer Seminar on Applied Mathematics, Cornell University, Jul. 26–Aug. 20, 1965.

Penrose, R. (1968). Structure of spacetime. See DeWitt and Wheeler (1968).

Penrose, R. (1969). Gravitational collapse: The role of general relativity. *Revista del Nuovo Cimento Numero Speziale 1*, 257–276. Reprinted in *General Relativity and Gravitation* 34(2002,7):1141–1165, doi:10.1023/A:1016534604511.

Penrose, R. (1972). *Techniques of Differential Topology in Relativity*. CBMS-NSF Regional Conference Series in Applied Mathematics. Philadelphia: Society for Industrial and Applied Mathematics. The notes of a lecture delivered by the author at Regional Conferences, 14–17 Jul 1970, at the University of Pittsburgh.

Penrose, R. (1973, December). Naked singularities. *Annals of the New York Academy of Sciences 224*, 125–134. Proceedings of the Sixth Texas Symposium on Relativistic Astrophysics. doi:10.1111/j.1749-6632.1973.tb41447.x.

Penrose, R. (1979). Singularities and time-asymmetry. See Hawking and Israel (1979), pp. 581–638.

Penrose, R. (1980). On Schwarzschild causality—a problem for 'Lorentz covariant' general relativity. In F. Tipler (Ed.), *Essays in General Relativity: A Festchrift for Abraham Taub*, Chapter 1, pp. 1–12. New York: Academic Press.

Penrose, R. (1989). Difficulties with inflationary cosmology. *Annals of the New York Academy Sciences 571*(1), 249–264. Proceedings of the Texas Symposium on Relativistic Astrophysics.

Penrose, R. (1998). The question of cosmic censorship. See Wald (1998), Chapter 5, pp. 103–112.

Penrose, R. (2011, March). Conformal treatment of infinity. *General Relativity and Gravitation 43*(3), 901–922. A reprint of the original 1964 paper given by Penrose at a conference. doi:10.1007/s10714-010-1110-5.

Penrose, R. and R. Floyd (1971, 08 February). Extraction of rotational energy from a black hole. *Nature 229*, 177–179. doi:10.1038/physci229177a0.

Penrose, R. and W. Rindler (1984). *Spinors and Spacetime: Two-Spinor Calculus and Relativistic Fields*, Volume 1. Cambridge: Cambridge University Press.

Pirani, F. (1962). Gauss's theorem and gravitational energy. See Lichnerowicz and Tonnelat (1962), pp. 85–91. Proceedings of a conference held at Royaumont in June, 1959.

Poisson, E. (2004). *A Relativist's Toolkit: The Mathematics of Black-Hole Mechanics*. Cambridge: Cambridge University Press.

Reichenbach, H. (1927[1958]). *The Philosophy of Space & Time*. New York City: Dover Publications, Inc. Translated by Maria Reichenbach and John Freund in 1957, from the original 1927 edition.

Riemann, B. (1854). Über die Hypothesen, welche der Geometrie zu Grunde liegen. Habilitationsschrift, Königlichen Gesellschaft der Wissenschaften zu Göttingen. English translation by Howard Stein (unpublished), "On the Hypotheses, Which Lie at the Basis of Geometry", available online at http://strangebeautiful.com/other-minds.html#riemann.

Rindler, W. (2006). *Relativity: Special, General and Cosmological* (Second ed.). Oxford: Oxford University Press. First edition published 2001.

Robinson, D. (1975). Uniqueness of the Kerr black hole. *Physical Review Letters 34*(14), 905–906. doi:10.1103/PhysRevLett.34.905.

Robinson, D. (1977). A simple proof of the generalization of Israel's theorem. *General Relativity and Gravitation 5*(8), 695–698. doi:10.1007/BF00756322.

Roman, T. (1988). On the "averaged weak energy condition" and Penrose's singularity theorem. *Physical Review D 37*(2), 546–548. doi:10.1103/PhysRevD.37.546.

Rovelli, C. (1991). What is observable in classical and quantum gravity? *Classical and Quantum Gravity 8*, 297–316.

Rovelli, C. (2000). Quantum spacetime: What do we know? In C. Callender and N. Huggett (Eds.), *Physics Meets Philosophy at the Quantum Scale*, Chapter 4, pp. 101–124. Cambridge: Cambridge University Press. Preprint available at arXiv:gr-qc/9903045v1.

Rovelli, C. (2002). GPS observables in general relativity. *Physical Review D 65*, 044017. Preprint available at arXiv:gr-qc/0110003v2.

Russell, B. (1997). *The ABC of Relativity* (fourth ed.). London: Routledge. First edition published 1925.

S., H. (1968). The existence of cosmic time functions. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences 308*, 433–435.

Schmidt, B. (1971). A new definition of singular points in general relativity. *General Relativity and Gravitation 1*, 269–280.

Schoen, R. and S.-T. Yau (1983). The existence of a black hole due to condensation of matter. *Communications in Mathematical Physics 90*(4), 575–579. doi:10.1007/BF01216187.

Schrödinger, E. (1950). *Space-Time Structure*. Cambridge Science Classics. Cambridge: Cambridge University Press. Reprinted in 1988.

Sciama, D. (1976). Black holes and their thermodynamics. *Vistas in Astronomy 19, Part 4*, 385–41. doi:10.1016/0083-6656(76)90052-0.

Senovilla, J. (1997). Singularity theorems and their consequences. *General Relativity and Gravitation 29*(5), 701–848. doi:10.1023/A:1018801101244. On Springer's website, this article is cited as being in volume 30 in the year 1998; on the article itself, however, is written volume 29, 1997; the issue number and page numbers are the same.

Senovilla, J. (2007). A singularity theorem based on spatial averages. *Pramana 69*(1), 31–48. doi:10.1007/s12043-007-0109-2. Preprint available at arXiv:gr-qc/0610127v3.

Senovilla, J. (2008, January). A new type of singularity theorem. In A. Oscoz, E. Mediavilla, and M. Serra-Ricart (Eds.), *Spanish Relativity Meeting—Encuentros Relativistas Españoles, ERE2007: Relativistic Astrophysics and Cosmology*, Volume 30 of *EAS Publications*, pp. 101–106. doi:10.1051/eas:0830009. Preprint available at arXiv:0712.1428 [gr-qc].

Shepley, L. and G. Ryan (1978). *Homogeneous Cosmological Models*. Princeton: Princeton University Press.

Siklos, S. (1979). Singularities and invariants. *General Relativity and Gravitation 10*, 1003–1004.

Siklos, S. (1981). Nonscalar singularities in spatially homogeneous cosmologies. *General Relativity and Gravitation 13*, 433–441.

Sklar, L. (1976). *Space, Time and Spacetime* (Paperback ed.). Berkeley: University of California Press.

Sklar, L. (1985). Inertia, gravitation, and metaphysics. In *Philosophy and Spacetime Physics*, Chapter 6, pp. 189–214. Berkeley: University of California Press. Originally published in *Philosophy of Science* 43(1976):1–23.

Smeenk, C. (2012a). Inflation and the origin of structure. Unpublished manuscript. Available on request from the author.

Smeenk, C. (2012b). The logic of cosmology revisited. Unpublished manuscript. Available on request from the author.

Smeenk, C. (2012c). Philosophy of cosmology. Unpublished manuscript. Available on request from the author.

Sorkin, R. (2005). Ten theses on black hole entropy. *Studies in History and Philosophy of Modern Physics 36*, 291–301.

Spivak, M. (1965). *Calculus on Manifolds*. Reading, MA: Addison-Wesley Publishing Co.

Spivak, M. (1979a). *A Comprehensive Introduction to Differential Geometry* (Second ed.), Volume 1. Houston: Publish or Perish Press. First edition published in 1970.

Spivak, M. (1979b). *A Comprehensive Introduction to Differential Geometry* (Second ed.), Volume 2. Houston: Publish or Perish Press. First edition published in 1970.

Stachel, J. (1989). Einstein's search for general covariance, 1912–1915. See Howard and Stachel (1989), pp. 63–100. A paper delivered to the Ninth International Conference on General Relativity and Gravitation, Friedrich-Schiller-Universität, Jena, 14–16 July 1980.

Stein, H. (1977). Some philosophical prehistory of general relativity. See Earman and Stachel (1977), pp. 3–49.

Stephani, H., D. Kramer, M. MacCallum, C. Hoenselaers, and E. Herlt (2009). *Exact Solutions of Einstein's Field Equations* (Second ed.). Cambridge Monographs in Mathematical Physics. Cambridge: Cambridge University Press. First edition published in 1981 by Stephani, Kramer and MacCallum.

Synge, J. (1957). *The Relativistic Gas*. Amsterdam: North-Holland Publishing Co.

Synge, J. (1960). *Relativity: The General Theory*. Amsterdam: North-Holland Publishing Co.

Synge, J. (1962). Tensorial integral conservation laws in general relativity. See Lichnerowicz and Tonnelat (1962), pp. 75–83. Proceedings of a conference held at Royaumont in June, 1959.

't Hooft, G. (1995). Quantum information and information loss in general relativity. arXiv:gr-qc/9509050. An elaborated version of a lecture held at the 5th International Symposium on Foundations of Quantum Mechanics in the Light of New Technology, Quantum Coherence and Decoherence, August 21–24, 1995, Adv. Res. Lab, Hitachi, Ltd., Hatoyama, Saitama (Tokyo), Japan.

Taub, A. (1979). Remarks on the symposium on singularities. *General Relativity and Gravitation 10*, 1009.

Teitelboim, C. (1972a). Nonmeasurability of the lepton number of a black hole. *Lettere al Nuovo Cimento 3*(10), 397–400. doi:10.1007/BF02826050.

Teitelboim, C. (1972b). Nonmeasurability of the quantum numbers of a black hole. *Physical Review D 5*(12), 2941–2954. doi:10.1103/PhysRevD.5.2941.

Thorne, K., R. Price, and D. MacDonald (Eds.) (1986). *Black Holes: The Membrane Paradigm*. New Haven, CT: Yale University Press.

Thorpe, J. (1977). Curvature invariants and space-time singularities. *Journal of Mathematical Physics 18*, 960–964.

Tipler, F. (1977a, September). Singularities and causality violations. *Annals of Physics 108*(1), 1–36. doi:10.1016/0003-4916(77)90348-7.

Tipler, F. (1977b, November). Singularities in conformally flat spacetimes. *Physics Letters A 64*(1), 8–10. doi:10.1016/0375-9601(77)90508-4.

Tipler, F. (1978). Energy conditions and spacetime singularities. *Physical Review D 17*(10), 2521–2528. doi:10.1103/PhysRevD.17.2521.

Tipler, F. (1979). The growth of curvature near a space-time singularity. *General Relativity and Gravitation 10*, 1005–1006.

Tipler, F., C. Clarke, and G. Ellis (1980). Singularities and horizons—A review article. In A. Held (Ed.), *General Relativity and Gravitation*, Volume 2, Chapter 4, pp. 97–206. New York: Plenum Press. 2 Volumes.

Tod, K. (2002). Isotropic cosmological singularities. In J. Frauendiener and H. Friedrich (Eds.), *The Conformal Structure of Space-Time: Geometry, Analysis, Numerics*, Number 604 in Lecture Notes in Physics, Chapter 6, pp. 123–134. Berlin: Springer-Verlag.

Torretti, R. (1996). *Relativity and Geometry*. Mineola, NY: Dover Publications, Inc.

Trautman, A. (1962). Conservation laws in general relativity. In L. Witten (Ed.), *Gravitation: An Introduction to Current Research*, pp. 169–198. New York: Wiley & Sons Press.

Trautman, A. (1965). Foundations and current problems of general relativity. In S. Deser. and K. Ford (Eds.), *Lectures on General Relativity*, Volume 1 of *Brandeis Summer Institute in Theoretical Physics*, pp. 1–248. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Unruh, W. and R. Wald (1982). Acceleration radiation and the Generalized Second Law of thermodynamics. *Physical Review D 25*(4), 942–958. doi:10.1103/PhysRevD.25.942.

Unruh, W. and R. Wald (1995, August). On evolution laws taking pure states to mixed states in quantum field theory. *Physical Review D 52*(4), 2176–2182. doi:10.1103/PhysRevD.52.2176. Preprint available at arXiv:hep-th/9503024v3.

Visser, M. (1997a, 04 April). Energy conditions in the epoch of galaxy formation. *Science 276*(5309), 88–90. doi:10.1126/science.276.5309.88. Preprint available at arXiv:gr-qc/9710010v2. Originally presented at the Eighth Marcel Grossmann Conference on General Relativity, Jerusalem, Israel, June 1997.

Visser, M. (1997b). General relativistic energy conditions: The Hubble expansion in the epoch of galaxy formation. *Physical Review D 56*, 7578–7587. doi:10.1103/PhysRevD.56.7578. Preprint available at arXiv:gr-qc/9705070.

Visser, M. (2005). Cosmography: Cosmology without the Einstein equation. *General Relativity and Gravitation 37*(9), 1541–1548. doi:10.1007/s10714-005-0134-8. Based on a talk delivered at ACRGR4, the 4th Australasian Conference on General Relativity and Gravitation, Monash University, Melbourne, January 2004. Preprint available at arXiv:gr-qc/0411131.

Wald, R. (1972). Electromagnetic fields and massive bodies. *Physical Review D 6*(6), 1476–1479. 10.1103/PhysRevD.6.1476.

Wald, R. (1973). On perturbations of a Kerr black hole. *Journal of Mathematical Physics 14*(10), 1453–1461. doi:10.1063/1.1666203.

Wald, R. (1984). *General Relativity*. Chicago: University of Chicago Press.

Wald, R. (1993). Black hole entropy is the Noether charge. *Physical Review D 47*, 3427–3431.

Wald, R. (1994). *Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics*. Chicago: University of Chicago Press.

Wald, R. (1997). 'Nernst theorem' and black hole thermodynamics. *Physical Review D 56*(10), 6467–6474. doi:10.1103/PhysRevD.56.6467. Preprint available at arXiv:gr-qc/9704008.

Wald, R. (Ed.) (1998). *Black Holes and Relativistic Stars*. Chicago: University of Chicago Press.

Wald, R. (1999a). Gravitation, thermodynamics and quantum theory. arXiv:gr-qc/9901033v1.

Wald, R. (1999b). The thermodynamics of black holes. arXiv:gr-qc/9912119v1.

Wald, R. and S. Gao (2001). "Physical process version" of the First Law and the Generalized Second Law for charged and rotating black holes. *Physical Review D 64*(8), 084020. doi:10.1103/PhysRevD.64.084020.

Wallace, D. (2010). Gravity, entropy, and cosmology: In search of clarity. *British Journal for the Philosophy of Science 61*(3), 513–540. doi:10.1093/bjps/axp048.

Weinberg, S. (1972). *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*. New York: Wiley and Sons Press.

Weinberg, S. (2008). *Cosmology*. Oxford: Oxford University Press.

Weyl, H. (1921). *Space-Time-Matter* (fourth ed.). New York: Dover Press. A 1952 reprint of the 1950 translation by H. Brose of the 1921 edition. The first edition published 1918.

Weyl, H. (1949). *Philosophy of Mathematics and Natural Science*. Princeton: Princeton University Press.

Will, C. (1993). *Theory and Experiment in Gravitational Physics* (Revised ed.). Cambridge: Cambridge University Press. The firsty edition was published in 1981.