

General Relativity

Course 2017-2018

General description of the course

This is a basic course on General Relativity, the relativistic theory of gravity in which we cover most of the basic topics covered in any standard introductory course (including the mathematical tools we need) except for cosmology, which is covered in a different course.

Good knowledge of Special Relativity, Classical Mechanics and Classical Field Theory is required and some knowledge of Differential Geometry is desirable. These topics will be reviewed during the course for the benefit of those students whose background is weaker, but it is clear that they must make an additional effort to reach the level needed to follow the rest of the course.

There are many good books on the subject. We will mainly follow Zee's (see below), but we will also draw information from many others. Lecture notes will be provided to the students.

Students should notice that the exam is scheduled very soon after the end of the lectures and that some important topics are covered in the last lectures. Thus, given the density of the lectures, the only way to make sure they will pass the exam is to be follow and study the lectures on a daily basis, making sure they do not leave any doubts unsolved before the next lecture. The teachers will be happy to help you solve those doubts if you come to their offices.

Recommended textbooks

1. ***Einstein Gravity in a Nutshell***, A. Zee, Princeton University Press (2013)
2. ***Gravitation***, C. Misner, K. Thorne & J.A. Wheeler, Freeman (1970)
3. ***General Relativity***, R. Wald, The University Chicago Press (1984)
4. ***Gravitation and Cosmology***, S. Weinberg, Addison Wesley (1978)
5. ***Gravity: Newtonian, Post-Newtonian, Relativistic***, Eric Poisson & Clifford Will, Cambridge University Press (2014)

The first book is the main reference of the course. The second book contains a huge deal of information on the subject. The third is a standard reference of a higher level (specially mathematically). The fourth is another standard reference, a bit outdated. The fifth deals with approximate solutions and it is very interesting from a phenomenological/astrophysical point of view.

Additional *recommended complementary reading* (**RCR**) is indicated next to some topics in the program. These include original references of an adequate technical level, popular reviews etc. Students are encouraged to become familiar with and explores the scientific literature through the many databases available at the IFT or open to everybody (like the [arXiv](#)). Some difficult to obtain references can be provided by the professors on demand.

Program

Common topics (24+7h)

(Topics in red will be covered only if there is enough time)

1. **(5+2) Introduction. Principle of Least Action in Special Relativity: fields and particles^{1,2,3,4,5}**
 - 1.1. A quick review of Special Relativity.
 - 1.1.1. The Principle of Special Relativity.
 - 1.1.2. Lorentz transformations. The Lorentz and Poincaré groups.⁶ Immediate consequences.
 - 1.1.3. Law of addition of velocities.
 - 1.1.4. Geometrization of Special Relativity: Minkowski spacetime.
 - 1.1.5. Mechanics in Minkowski spacetime: momentum, energy etc.
 - 1.2. Relativistic particles and the Principle of Least Action.
 - 1.2.1. Review of the Principle of Least Action for a non-relativistic particle.⁷
 - 1.2.1.1. The Lagrangian and Euler-Lagrange equations.
 - 1.2.1.2. Conserved quantities.
 - 1.2.1.3. The action and the Principle of Least Action.
 - 1.2.1.4. First Noether theorem. Conserved quantities.
 - 1.2.1.5. Energy conservation.
 - 1.2.2. Actions for free massive relativistic particles.⁸

¹ **RCR:** *Special Relativity: a First Encounter*, Domenico Giulini, Oxford University Press 2005.

² **RCR:** *An Illustrated Guide to Relativity*, Tatsu Takeuchi, Cambridge University Press, 2010.

³ **RCR:** *Special Relativity: From Einstein to Strings*, Patricia M. Schwarz & John H. Schwarz, Cambridge University Press, 2004.

⁴ **RCR:** [Part I, Special Relativity](#), G.W. Gibbons.

⁵ **RCR:** [Einstein's comprehensive 1907 essay on relativity Part I](#), H.M. Schwarz, *American Journal of Physics* **45**, (1977) 512.

⁶ **RCR:** [Getting the Lorentz transformations without requiring an invariant speed](#), A. Pelissetto and M. Testa, *American Journal of Physics* **83** (2015) 338-340.

⁷ **RCR:** *Classical Dynamics: A Contemporary Approach*, J.V. Jose and E.J. Saletan, Cambridge University Press 1998. Or any other good book in classical mechanics.

⁸ **RCR:** for this topics and relativistic fields: *Electrodynamics and Classical Theory of Fields and Particles*, A.O. Barut, Dover. Other books on classical or quantum field theory can also be useful.

- 1.2.3. Actions for free massless relativistic particles.
 - 1.2.4. The third law of dynamics: interactions.
 - 1.3. Relativistic fields.
 - 1.3.1. Generalities
 - 1.3.2. The scalar field.
 - 1.3.2.1. Transformations.
 - 1.3.2.2. Field strength. Scalar potentials.
 - 1.3.2.3. Action and field equations.
 - 1.3.2.4. The energy-momentum tensor of the scalar field.
 - 1.3.2.5. Massive particle coupled to a scalar field.
 - 1.3.3. The vector field.
 - 1.3.3.1. Transformations.
 - 1.3.3.2. Field strength. Scalar potentials.
 - 1.3.3.3. Action and Maxwell equations in vacuum.
 - 1.3.3.4. The energy-momentum tensor of the Maxwell field.
 - 1.3.3.5. Massive particle coupled to the Maxwell field. Electric charge.
 - 1.4. Relativistic fluids
 - 1.4.1. Generalities
 - 1.4.2. Newtonian perfect fluids.
 - 1.4.3. Relativistic perfect fluids. Energy-momentum tensor.
 - 1.4.4. Fundamental fields as fluids.
2. **(2+1) Equivalence and Covariance Principles⁹**
- 2.1. The Weak Equivalence Principle.¹⁰
 - 2.1.1. Inertial and (active and passive) gravitational masses.
 - 2.1.2. The Weak Equivalence Principle and its experimental status.^{11, 12}
 - 2.1.3. Implications: no privileged reference frames. The General Principle of Relativity.
 - 2.2. The Einsteinian Equivalence Principle
 - 2.2.1. Statement of the principle and consequences.
 - 2.2.2. Experimental status.
 - 2.3. The Strong Equivalence Principle.
 - 2.3.1. Consistency of Special-Relativistic gravity and self-interaction.
 - 2.3.2. Statement of the principle and consequences.

⁹ RCR: [Nonequivalence of equivalence principles](#), Eolo Di Casola, Stefano Liberati , Sebastiano Sonego, *Am.J.Phys.* **83** (2015) 39.

¹⁰ RCR: [Einstein's comprehensive 1907 essay on relativity Part I](#), H.M. Schwarz, *American Journal of Physics* **45**, (1977) 512.

¹¹ RCR: [Test of the equivalence principle using a rotating torsion balance](#), Stephan Schlamminger, K.-Y. Choi, T.A. Wagner, J.H. Gundlach, E.G. Adelberger, *Phys.Rev.Lett.* **100** (2008) 041101

¹² RCR: [Torsion-balance tests of the weak equivalence principle](#), T.A. Wagner, S. Schlamminger, J.H. Gundlach, E.G. Adelberger, *Class.Quant.Grav.* **29** (2012) 184002

- 2.3.3. Experimental status^{13, 14, 15}
- 2.4. First experimental consequences of the Equivalence Principle.
 - 2.4.1. Motion of freely falling particles. Gravitational forces. The affine connection.
 - 2.4.2. The Newtonian limit.
 - 2.4.3. Gravitational time dilation and redshift.¹⁶
- 2.5. The Principle of General Covariance.
 - 2.5.1. Statement of the PGC and relation to the EP.

3. (4+1) General Covariance and Differential Geometry

- 3.1. Differential manifolds and general coordinate transformations¹⁷
- 3.2. Tensor fields
 - 3.2.1. (Contravariant) vectors
 - 3.2.2. 1-forms (or covariant vectors)
 - 3.2.3. General tensors
 - 3.2.4. Parallel transport, connections and covariant derivatives
 - 3.2.4.1. Auto-parallel curves
 - 3.2.4.2. Ricci identities: torsion and curvature
 - 3.2.5. Differential forms
 - 3.2.5.1. Exterior product and exterior derivative
 - 3.2.5.2. Volume forms and integration
 - 3.2.5.3. Stokes theorem
 - 3.2.6. Lie derivatives
- 3.3. (Pseudo-) Riemannian manifolds
 - 3.3.1. The metric field (and why is it specially important)
 - 3.3.2. Relation between covariant and contravariant indices
 - 3.3.3. Tensor densities: the Levi-Civita symbol.
 - 3.3.4. The Hodge dual
 - 3.3.5. Integration in (pseudo-) Riemannian manifolds
 - 3.3.6. Covariant derivatives in (pseudo-) Riemannian manifolds
 - 3.3.6.1. Non-metricity

¹³ RCR: [Improved Test of the Equivalence Principle for Gravitational Self-Energy](#), S. Baeßler, B. R. Heckel, E. G. Adelberger, J. H. Gundlach, U. Schmidt, and H. E. Swanson, Phys. Rev. Lett. **83** (1999) 3585.

¹⁴ RCR: [Equivalence Principle for Massive Bodies. 1. Phenomenology](#), K. Nordtvedt, Phys. Rev. **169** (1968) 014-1016.

¹⁵ RCR: [Equivalence Principle for Massive Bodies. 2. Theory](#), K. Nordtvedt, Phys. Rev. **169** (1968) 1017-1025.

¹⁶ RCR: [Einstein's comprehensive 1907 essay on relativity Part I](#), H.M. Schwarz, American Journal of Physics **45**, (1977) 512.

¹⁷ RCR: [Geometry, Topology and Physics](#), Second Edition (Graduate Student Series in Physics), M. Nakahara, Taylor & Francis 2003. There are many other good books on differential geometry at different levels.

- 3.3.6.2. Torsion¹⁸
- 3.3.6.3. The Levi-Civita connection.
- 3.3.6.4. Ricci identities and the Riemann curvature tensor
- 3.3.6.5. Bianchi identities
- 3.3.6.6. Ricci tensor, Ricci scalar and the Einstein tensor.

3.3.7. Geodesics

4. (T, 4+1) General Relativity

- 4.1. Invariant actions in (pseudo-)Riemannian spaces.
 - 4.1.1. Generalities
 - 4.1.2. Scalar field in a background metric. Minimal coupling
 - 4.1.3. Higher derivatives and boundary terms
 - 4.1.4. More on minimal coupling
 - 4.1.5. The electromagnetic field in a background metric.
 - 4.1.6. The gravitational energy-momentum tensor
 - 4.1.6.1. Rosenfeld's prescription.
 - 4.1.6.2. The PGC and the on-shell-vanishing divergence of the gravitational energy-momentum tensor
 - 4.1.6.3. The PGC, the second Noether theorem and the Noether identity for the gravitational field equations.
- 4.2. The Einstein-Hilbert action¹⁹
 - 4.2.1. Candidates to gravitational action.²⁰ Coupling constant.
 - 4.2.2. The Einstein equations in vacuum
 - 4.2.3. The York-Gibbons-Hawking boundary term^{21, 22, 23}
 - 4.2.4. Noether's second theorem and the contracted Bianchi identity.
 - 4.2.5. The cosmological constant term.
 - 4.2.6. Coupling to matter fields.
 - 4.2.7. Coupling to fluids
 - 4.2.8. Coupling to point-particles.
 - 4.2.8.1. Actions.
 - 4.2.8.2. Motion of free particles in gravitational fields: geodesics^{24, 25}

¹⁸ RCR: [Constraining Torsion with Gravity Probe B](#), Yi Mao, Max Tegmark, Alan H. Guth, Serkan Cabi, Phys. Rev. D**76** (2007) 104029

¹⁹ RCR: [On the “Derivation” of Einstein’s Field Equations](#), S. Chandrasekhar, Am. J. Phys. **40**, (1972) 224.

²⁰ RCR: [The Einstein tensor and its generalizations](#), D. Lovelock, Journal of Mathematical Physics **12** (1971) 498.

²¹ RCR: [Role of conformal three-geometry in the dynamics of gravitation](#). J.W. York Jr., Physical Review Letters. **28** (1972) 1082.

²² RCR: [Action integrals and partition functions in quantum gravity](#), G.W. Gibbons and S.W. Hawking, Physical Review D. **15** (1977) 2752.

²³ RCR: [The gravitational Hamiltonian, action, entropy and surface terms](#), Class. Quantum Grav. **13** (1996) 1487.

²⁴ RCR: [The Gravitational Equations and the Problem of Motion](#), A. Einstein, L. Infeld and B. Hoffmann, Annals of Mathematics, Second Series, **39**, No. 1 (1938), 65-100.

²⁵ RCR: [Equations of Motion in General Relativity](#), A. Papapetrou, Proc. Phys. Soc. A **64** (1951) 57.

- 4.2.8.3. Proper acceleration
 - 4.2.8.4. Special coordinates
 - 4.2.8.5. Geodesic deviation
 - 4.2.8.6. Conserved quantities and integration of the equations of motion:
 - 4.2.8.6.1. Killing vectors and isometry groups
 - 4.2.8.6.2. Isometries and Noether charges
 - 4.3. The weak field limit of the Einstein equations.^{26 27}
 - 4.3.1. The field created by a massive point-particle at rest.
 - 4.3.2. Point-particles coupled to weak gravitational fields.
 - 4.3.3. Gravitational waves
 - 4.4. Covariant generalizations of General Relativity with higher-curvature and derivative terms.²⁸²⁹
 - 4.4.1. The Jordan-Brans-Dicke theory^{30 31},
 - 4.4.2. f(R) theories and their equivalence to the Jordan-Brans-Dicke theory with a scalar potential.^{32 33 34},
- 5. (R, 3+1) Some exact solutions**
- 5.1. General considerations on the search of exact solutions of the Einstein equations
 - 5.1.1. Symmetry and special coordinates
 - 5.2. Vacuum solutions
 - 5.2.1. The Schwarzschild solution^{35 36 37 38 39},
 - 5.2.2. Plane waves
 - 5.3. Non-vacuum solutions
 - 5.3.1. The interior Schwarzschild solution
 - 5.3.2. Some cosmological solutions: (anti-)De Sitter.

²⁶ RCR: [General Relativity and Flat Space. I](#), N. Rosen, Phys. Rev. **57** (1940) 147

²⁷ RCR: [General Relativity and Flat Space. II](#), N. Rosen, Phys. Rev. **57** (1940) 150.

²⁸ RCR: [Classical Gravity with Higher Derivatives](#), K. S. Stelle, Gen.Rel.Grav. **9** (1978) 353-371.

²⁹ RCR: [Avoiding Dark Energy with 1/R Modifications of Gravity](#), R. P. Woodard, [The Invisible Universe: Dark Matter and Dark Energy, Lecture Notes in Physics](#), **720**, 403-433

³⁰ RCR: [Mach's Principle and a Relativistic Theory of Gravitation](#), C.H. Brans and R Dicke, Phys. Rev. **124** (1961) 925.

³¹ RCR: [Jordan-Brans-Dicke Theory](#), Carl H. Brans, Scholapedia, **9(4)** (2014) 31358.

³² RCR: [f\(R\) Theories Of Gravity](#), T.P. Sotiriou , V. Faraoni, Rev.Mod.Phys. **82** (2010) 451-497.

³³ RCR: [f\(R\) theories](#), A. De Felice, S. Tsujikawa, Living Rev.Rel. **13** (2010) 3..

³⁴ RCR: [Unified cosmic history in modified gravity: from F\(R\) theory to Lorentz non-invariant models](#) S. Nojiri, S.D. Odintsov, Phys.Rept. **505** (2011) 59-144.

³⁵ RCR: ["Golden Oldie": On the Gravitational Field of a Mass Point according to Einstein's Theory](#), K. Schwarzschild, Gen. Rel. Grav. **35** (2003) 951.

³⁶ RCR: [Editor's Note: On the Gravitational Field of a Mass Point According to Einstein's Theory by K. Schwarzschild](#), S. Antoci, D.-E. Liebscher, Gen. Rel. Grav. **35** (2003) 945-950.

³⁷ RCR: ["Golden Oldie": The Field of a Single Centre in Einstein's Theory of Gravitation, and the Motion of a Particle in That Field](#), J. Droste, Gen. Rel. Grav. **34** (2002) 1545-1563.

³⁸ RCR: [Editor's Note: The Field of a Single Centre in Einstein's Theory of Gravitation, and the Motion of a Particle in That Field](#), T. Rothman, Gen. Rel. Grav. **34** (2002) 1541.

³⁹ RCR: [The Schwarzschild solution: corrections to the editorial note](#), J.M.M. Senovilla, Gen. Rel. Grav. **39** (2007) 685-693.

6. (3+1) Experimental tests of GR^{40, 41, 42, 43}

- 6.1. Motion in the external Schwarzschild geometry.
 - 6.1.1. Geodesic motion in the Schwarzschild field⁴⁴
 - 6.1.2. Conserved quantities.
 - 6.1.3. Orbits.
- 6.2. Classical Solar System tests.
 - 6.2.1. Deflection of light by the Sun.^{45, 46, 47}
 - 6.2.2. Gravitational redshift^{48, 49, 50}
 - 6.2.3. Gravitational lensing⁵¹
 - 6.2.4. Precession of perihelia⁵²
 - 6.2.5. Radar echo delay^{53, 54}
 - 6.2.6. Cassini experiment⁵⁵
- 6.3. Introduction to the PPN approximation.
 - 6.3.1. The PPN formalism in brief.
 - 6.3.2. PPN approximation to General Relativity.
 - 6.3.3. Precession of perihelia.
 - 6.3.4. Precession of orbiting gyroscopes.
- 6.4. Gravitational waves
 - 6.4.1. Generalities: production and propagation^{56, 57}

⁴⁰ RCR: *Was Einstein Right?* C. M. Will, (Basic Books, New York, (1986).

⁴¹ RCR: *Theory and experiment in gravitational physics*, C.M. Will, Cambridge University Press (1993)

⁴² RCR: [The Confrontation between general relativity and experiment](#), Clifford M. Will, Living Rev.Rel. **4** (2001) 4

⁴³ RCR: [Experimental Tests of General Relativity](#), S. Turyshev, Annual Review of Nuclear and Particle Science, **58** (2008) 207-248

⁴⁴ RCR: ["Golden Oldie": The Field of a Single Centre in Einstein's Theory of Gravitation, and the Motion of a Particle in That Field](#), J. Droste, Gen. Rel. Grav. **34** (2002) 1545–1563.

⁴⁵ RCR: [A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations Made at the Total Eclipse of May 29, 1919](#), F.W. Dyson, A.S. Eddington , C. Davidson, Phil.Trans.Roy.Soc.Lond. **A220** (1920) 291-333.

⁴⁶ RCR: [Measurement of the Solar Gravitational Deflection of Radio Waves Using Very-Long-Baseline Interferometry](#), D.E. Lebach, B.E. Corey, I.I. Shapiro, M.I. Ratner, J.C. Webber, A.E.E. Rogers, J.L. Davis, T.A. Herring, Phys.Rev.Lett. **75** (1995) 1439-1442

⁴⁷ RCR: [Total eclipse 2017](#)

⁴⁸ RCR: [Apparent Weight of Photons](#), R. V. Pound and G. A. Rebka, Jr., Phys. Rev. Lett. **4** (1960) 337

⁴⁹ RCR: [Weighing Photons, I](#), R.V. Pound, Physics in Perspective **2** (2000) 224.

⁵⁰ RCR: [Weighing Photons, II](#), R.V. Pound, Physics in Perspective **3** (2001) 4.

⁵¹ RCR: [Relativistic deflection of background starlight measures the mass of a nearby white dwarf star](#), K.C. Sahu et al, Science **356** (2017) 1046-1050.

⁵² RCR: [The Wikipedia page on the general-relativistic two-body problem](#).

⁵³ RCR: [Fourth test of general relativity](#), I. Shapiro, Physical Review Letters. **13** (1964) 789–791.

⁵⁴ RCR: [Viking relativity experiment: Verification of signal retardation by solar gravity](#), R.D. Reasenberg, I.I. Shapiro, P.E. MacNeil, R.B. Goldstein, J.C. Breidenthal, J.P. Brenkle, D.L. Cain, T.M. Kaufman, T.A. Komarek, A.I. Zygielbaum, Astrophys.J. **234** (1979) L219-L221.

⁵⁵ RCR: [A test of general relativity using radio links with the Cassini spacecraft](#), B. Bertotti, L. Iess & P. Tortora, Nature **425** (2003) 374-376.

⁵⁶ RCR: [Post-newtonian generation of gravitational waves](#), L. Blanchet and T. Damour, Annales de l'I.H.P. Physique théorique, **50** (1989) 377-408.

- 6.4.2. Detection⁵⁸
- 6.5. Binary pulsars tests.
- 6.6. The General Relativity versus other metric theories of gravity.
- 7. (3) The Schwarzschild black hole.
 - 7.1. The singularity at the Schwarzschild radius
 - 7.1.1. Curvature invariants
 - 7.1.2. Alternative coordinate systems.
 - 7.1.3. Observers in free fall.
 - 7.1.4. The Kruskal-Szekeres maximal analytical extension⁵⁹
 - 7.1.5. Einstein-Rosen bridges and wormholes^{60, 61}
 - 7.2. Penrose diagrams.
 - 7.2.1. Minkowski
 - 7.2.2. Schwarzschild
 - 7.2.3. Simple model of gravitational collapse

Temas Optativos (8+3)

Bloque A

1. Colapso gravitacional. Objetos compactos (estrellas de neutrones, enanas blancas).
2. Astrofísica de agujeros negros. Búsqueda por métodos observacionales.
3. Emisión de radiación ultraenergética (en las vecindades de objetos astronómicos ultrarrelativistas).

Bloque B

1. (T, 2) Black-hole physics^{62, 63}

⁵⁷ RCR: [Gravitational radiation damping of compact binary systems to second postNewtonian order](#), Luc Blanchet , Thibault Damour, Bala R. Iyer, Clifford M. Will, Alan.G. Wiseman, Phys.Rev.Lett. **74** (1995) 3515-3518

⁵⁸ RCR: [LIGO: The Laser interferometer gravitational wave observatory](#), A. Abramovici et al., Science **256** (1992) 325-333.

⁵⁹ RCR: [Maximal Extension of Schwarzschild Metric](#), M. D. Kruskal, Phys. Rev. **119** (1960) 1743

⁶⁰ RCR: [The Particle Problem in the General Theory of Relativity](#), A. Einstein, N. Rosen, Physical Review. **48** (1935) 73-77.

⁶¹ RCR: [Cool horizons for entangled black holes](#), Maldacena, Juan; Susskind, Leonard (2013). . Fortsch. Phys. **61**: 781-811.

⁶² RCR: [A Relativist's Toolkit](#), E. Poisson, Cambridge University Press 2004.

⁶³ RCR: [Black Hole Physics, Basic Concepts and New Developments](#), V. Frolov, I. Novikov, Springer Verlag 1998.

- 1.1. More on the Schwarzschild black hole
 - 1.1.1. The negative-mass Schwarzschild solution
 - 1.1.2. Apparent horizon and trapped surfaces
 - 1.1.3. The Vaidya spacetime
 - 1.1.4. Killing horizons and bifurcation spheres
- 1.2. The Reissner-Nordström black hole solution⁶⁴
 - 1.2.1. Construction of the solution
 - 1.2.2. Identification of the mass and charge
 - 1.2.3. Horizons and extremality
 - 1.2.4. Maximal analytical extension and Penrose diagram
 - 1.2.5. The Papapetrou-Majumdar solutions
- 1.3. The event horizon.
 - 1.3.1. Definition and characterization
 - 1.3.2. Surface gravity
 - 1.3.3. Area, topology
- 1.4. Thermodynamics of black holes.
 - 1.4.1. Classical laws of black-hole dynamics⁶⁵
 - 1.4.2. Hawking radiation and temperature^{66 67 68},
 - 1.4.3. Bekenstein-Hawking entropy^{69 70},

Calendar

TOM: theory by Tomás Ortín Miguel

ARV: problems by Alejandro Ruipérez Vicente

OPT: theory options A or B. (A: Rosa Domínguez Tenreiro, B: TOM)

Tema	Hora	Fecha	TOM	ARV	OPT
Tema 1	1	lunes 11 septiembre	1		
	2	“ “	2		

⁶⁴ **RCR:** *The large scale structure of spacetime*, S.W. Hawking and G.F.R. Ellis, Cambridge University Press 1973.

⁶⁵ **RCR:** [*The four laws of black hole mechanics*](#), J. M. Bardeen, B. Carter, and S. W. Hawking, *Comm. Math. Phys.* **31** (1973) 161-170.

⁶⁶ **RCR:** [*Particle creation by black holes*](#), *Communications in Mathematical Physics*, **43** (1974) 199–220

⁶⁷ **RCR:** [*Black holes and thermodynamics*](#), S. W. Hawking, *Phys. Rev. D* **13** (1976) 191

⁶⁸ **RCR:** [*Breakdown of predictability in gravitational collapse*](#), S. W. Hawking, *Phys. Rev. D* **14** (1976) 2460.

⁶⁹ **RCR:** [*Black Holes and Entropy*](#), Jacob D. Bekenstein, *Phys. Rev. D* **7** (1973) 2333.

⁷⁰ **RCR:** [*Generalized second law of thermodynamics in black hole physics*](#), Jacob D. Bekenstein, *Phys. Rev. D* **9** (1974) 3292-3300.

	3	martes 12 septiembre	3		
	4	miércoles 13 septiembre		1	
	5	lunes 18 septiembre	4		
	6	" "	5		
	7	martes 19 septiembre		2	
Tema 2	8	miércoles 20 septiembre	6		
	9	lunes 25 septiembre	7		
	10	" "		3	
Tema 3	11	martes 26 septiembre	8		
	12	miércoles 27 septiembre	9		
	13	lunes 2 octubre	10		
	14	" "	11		
	15	martes 3 octubre		4	
Tema 4	16	miércoles 4 octubre	12		
	17	lunes 9 octubre	13		
	18	" "	14		
	19	martes 10 octubre	15		
	20	miércoles 11 octubre		5	
Tema 5	21	lunes 16 de octubre	16		
	22	" "	17		
	23	martes 17 octubre	18		
	24	miércoles 18 octubre		6	
Tema 6	25	lunes 23 octubre	19		
	26	" "	20		

	27	martes 24 octubre	21		
	28	miércoles 25 octubre		7	
Tema 7	29	lunes 30 octubre	22		
	30	“ “	23		
	31	martes 31 octubre	24		
Optativas	32	lunes 6 noviembre			1
	33	“ “			2
	34	martes 7 noviembre			3
	35	miércoles 8 noviembre		1 Opt	
	36	lunes 13 noviembre			4
	37	“ “			5
	38	martes 14 noviembre			6
	39	miércoles 15 noviembre		2 Opt	
	40	lunes 20 noviembre			7
	41	“ “			8
	42	martes 21 noviembre		3 Opt	
	43	miércoles 22 noviembre		questions-doubts	
		lunes 27 noviembre		Examen	