Approval date: 28/06/2024

COURSE GUIDE

Physics of Complex Systems (26711I2)

Grado (Bachelor's Degree)	Grado en Física	Branch	Sciences
Module	Física Computacional y de los Sistemas Complejos	Subject	Física de los Sistemas Complejos

Year of study	4º	Semester	2º	ECTS Credits	6	Course type	Elective course

PREREQUISITES AND RECOMMENDATIONS

General knowledge of Mathematics and Physics (particularly, Mechanics) is required, as acquired, for example, in the basic and mandatory subjects of the first courses of the degree in Physics. It would also be advisable to have taken "Computational Physics", an optional third-year course, as well as third-year Statistical Physics.

BRIEF DESCRIPTION OF COURSE CONTENT (According to the programme’s verification report)

Introduction. Complexity. Chaos. Fractal geometry. Scale invariance. Collective or cooperative phenomena. Critical phenomena. Pattern formation.

SKILLS

GENERAL SKILLS

- CG01 - Skills for analysis and synthesis
- CG02 - Organisational and planification skills
- CG03 - Oral and written communication
- CG04 - Conocimientos de informática relativos al ámbito de estudio
- CG05 - Skills for dealing with information
- CG06 - Problem solving skills
- CG08 - Critical thinking
- CG09 - Autonomous learning skills
- CG10 - Creativity

SUBJECT-SPECIFIC SKILLS

- CE01 - Knowing and understanding the phenomena of the most important physical

theories
- CE02 - Estimating the order of magnitud in order to interpret various phenomena
- CE05 - Modelling complex phenomena, translating a physical problem into mathematical language
- CE08 - Utilizar herramientas informáticas para resolver y modelar problemas y para presentar sus resultados.

LEARNING OUTCOMES

By this semester, the student already knows the microscopic and macroscopic descriptions of physics as provided, respectively, by Classical and Quantum Mechanics as well as the basic concepts of Thermodynamics and Statistical Physics, which rigorously relate these descriptions in the case of systems in thermodynamic equilibrium. However, thermodynamic equilibrium is a special circumstance that usually does not occur in the cases that are currently of most interest to Science, such as, for example, when turbulent regimes are established in a fluid, or when chemical compounds grouped together to achieve the first hint of independent life, or the nervous system achieves high-level information processing functions through the coordination of individual groups of neurons, or epidemics spread through a network of interactions. The concept of a complex system, capable of showing a fascinating phenomenology due to cooperation between elements, is then relevant. The recent study in physics of these complex systems has led to the development of powerful analysis methods that rely on computing and has generated or renewed concepts, all of which transcend the boundaries of physics to invade the foundations of other sciences, including biology and sociology. This is the situation that the course aims to describe, while also intending to help the student to:

1. Develop their skills to analyze and capture the essentials in natural systems and processes through algorithms, thus learning to effectively and accurately solve various problems,
2. Use computers creatively in modeling situations of interest in science, technology, and management, and
3. Face, if they wish to do so, the challenges that current research in public or private centers can pose once they graduate.

PLANNED LEARNING ACTIVITIES

THEORY SYLLABUS

1. Introduction. Complexity. Order and entropy in nature. Cooperative effects in statistical physics. Scales and levels of description. Non-linearity. Predictability. Measures of complexity.
2. Theory of dynamic systems. Introduction to the theory of dynamic systems and chaos (Poincaré. Lorenz. May. Feigenbaum). Non-linear maps. Fixed points, limit cycles, and strange attractors. Stability theory in one-dimensional and two-dimensional differential equations. Bifurcation and catastrophe theory. Lyapunov coefficients. Universality. Integrability and Hamiltonian chaos.
3. Scale invariance. Power laws. Mechanisms of power law generation. Fractal geometry. Regularity, randomness, and self-similarity. Hausdorff or fractal dimension. (Multifractality). Roughness and self-affine structures.
4. Theory of stochastic processes. Brief historical introduction. Brownian motion. Random walker. Einstein's theory. Perrin's experiments. Markov processes. Master equation.

Stochastic equations: Langevin and Fokker Planck. Path integrals. Levy flights.
5. Phase transition theory (I): Percolation. Scale invariance at the critical point. Introduction to the renormalization group. Dynamic percolation (forest fires). Directed percolation and the contact process.
6. Phase transition theory (II): Guggenheim curve and universality. Lattice models (Heisenberg, XY, etc.). Ising model. Spontaneous symmetry breaking. Order parameter and control parameter. Correlations and fluctuations. Critical exponents and scaling laws. Mean field theory. Ginzburg Landau theory. Ginzburg's criterion. Kadanoff blocks and real space renormalization.
7. Self-organization and criticality. Sandpiles. Earthquakes. Criticality in biology.
8. Other concepts that will be taught in specialized seminars: Introduction to the theory of complex networks. Evolutionary game theory. Applications: Neuroscience, Theoretical and Evolutionary Ecology, Systems Biology, etc.

PRACTICAL SYLLABUS

A supervised research work will be developed on some of the points covered by the theoretical syllabus.

RECOMMENDED READING

ESSENTIAL READING

- D. Sornette, "Critical Phenomena in Natural Sciences", Springer 2009.
- J. Sethna, "Entropy, Order parameters and Complexity". Oxford 2015.
- J.J. Binney et al. "The theory of Critical Phenomena". Oxford. 1999.
- S.H. Strogatz, "Non-linear dynamics and Chaos", Addison Wisley 2012.
- A. Fuchs, "Nonlinear dynamics in complex systems", Springer 2013.
- K. Christensen and N.R. Moloney, "Complexity and Criticality", Imperial College, London 2005.
- R.J. Creswick et al., "Introduction to Renormalization Group Methods in Physics", Wiley, NY 1992.
- J. Marro and R. Dickman, "Nonequilibrium Phase Transitions in Lattice Systems". Cambridge 2005.
- C.W. Gardiner, "Hanbdbook of stochastic methods", Springer Verlag, 2000.
- N.G. van Kampen, "Stochastic processes in Physics and Chemistry", Springer, 2004

COMPLEMENTARY READING

- M. Newman, "Networks: An introduction", Oxford 2011.
- A. Pikovsky et al. Synchronization: A universal concept in nonlinear sciences. Cambridge 2003.
- E. Ott, Chaos and dynamical systems, Cambridge, 2012.
- H. J. Jensen, "Self-Organized Criticality", Cambridge Univ. Press 1998.
- P. Krapivsky, S. Redner, E. Ben-Naim, "A kinetic view of Statistical Physics", Cambridge 2010.

TEACHING METHODS

- MD01 - Theoretical classes

ASSESSMENT METHODS (Instruments, criteria and percentages)

ORDINARY EXAMINATION DIET

The student must prove uniform knowledge of all the material, as is acquired by actively participating in class, so continuous attendance and problem-solving are essential parts of the evaluation. Furthermore, she/he must delve into one of the characteristic topics of the subject, which can be achieved by doing supervised personal work. There is evaluation throughout the course and, at the end of it, through the oral and/or written presentations that are determined between students and teacher.
Assessment: Research work: 2/3 of the final grade. Submitted problems, exercises, and continuous work 1/3.
The supervised personal work can be exchanged, in agreement with the teacher, for a final exam that will be valued in the same way.

EXTRAORDINARY EXAMINATION DIET

The student must demonstrate uniform knowledge of all the material. To certify such knowledge, the student will undergo a single final exam (probably oral). Alternatively, if the student so wishes, they can be evaluated through the points accumulated by a continuous assessment during the course, plus points for supervised research work.
Assessment: Research work: 2/3 of the final grade. Submitted problems, exercises, and work delivery 1/3.

SINGLE FINAL ASSESSMENT (evaluación única final)

For those who opt for the final single evaluation or the extraordinary one, these will contain the tests that the professor deems appropriate (preferably an exam or oral exam) in order to certify that the student has acquired all the general and specific competencies, and the student can achieve the maximum grade.

ADDITIONAL INFORMATION

Consult with the professors for more details about the course.
Información de interés para estudiantado con discapacidad y/o Necesidades Específicas de Apoyo Educativo (NEAE): Gestión de servicios y apoyos (https://ve.ugr.es/servicios/atencion-social/estudiantes-con-discapacidad).