GHENT UNIVERSITY

Course Specifications

Valid as from the academic year 2024-2025

Complexity and Criticality (C004106)

Course size *(nominal values; actual values may depend on programme)*

Credits 6.0 **Study time 180 h**

Course offerings and teaching methods in academic year 2024-2025

A (semester 2)	English	Gent	independent work seminar lecture
B (semester 2)	Dutch	Gent	seminar independent work lecture

Lecturers in academic year 2024-2025

Ryckebusch, Jan	WE05	lecturer-in-charge

Offered in the following programmes in 2024-2025	crdts	offering
Master of Science in Teaching in Science and Technology(main subject Physics and Astronomy)	6	A
Master of Science in Engineering Physics	6	B
Master of Science in Engineering Physics	6	A
Master of Science in Physics and Astronomy	6	A
Master of Science in Physics and Astronomy	6	A
Exchange Programme in Physics and Astronomy (Master's Level)	6	A

Teaching languages

English, Dutch

Keywords

Complexity, criticality, emergence, unversality, algorithms, high-level features of complex systems

Position of the course

This course aims at providing an advanced treatment of the numerical and analytical methods that can be used to extract the high-level features of complex sytems consisting of many interacting units. Central issues are the concepts of complexity, emergence, coarse graining, criticality, metastability and phases. It is shown how these concepts can be used to reach a deeper level of understanding of materials, of biological systems and of socio-economic systems. The approximation methods for complex systems that are introduced include numerical algorithms, perturbation theory, mean-field theory, scaling ansatz, and the real-space renormalization group.

Contents

The course is centered arount five topics:
(i) **Ising model** *(phases, review of equilibrium statistical mechanics, magnetization, response functions, spin-spin correlation function, critical temperature, mean-field and perturbation theory of the Ising model, Landau theory of continuous phase transitions, Widom scaling ansatz, universal critical exponents, order parameters, Ginzburg criterion, real-space renormalization theory, order-disorder transitions in alloys, fluctuation-dissipation theorem, Wang-Landau sampling, Markov chain Monte Carlo simulation methods, the connection*

between magnets and fluids, nucleation)

(ii) **Percolation model** *(definition, cluster number density, average cluster size, selfsimilarity, fractal dimension, correlation length, order parameter, real-space renormalization, fixed points, coarse graining, algorithms to identify clusters in networks, statistical methods designed to deal with phenomena that extend over many scales)*

(iii) **Self-organised criticality and non-equilibrium systems** *(dynamic equilibrium, sandpile metaphor, Bak-Tang-Wiesenfeld model, mean-field theory of the BTW Model, examples of scale-free behaviour in nature, alternate dynamics that describes scale-free behaviour in nature)*

(iv) **Dense gases and liquids** *(Van-der Waals theory, perturbation theory, effective interactions, cumulant expansions, virial expansions, distribution and correlation functions, cluster diagrams, fluctuation-dissipation theorem, velocity-autocorrelation functions)*

(v) **Econophysics** *(crashes as critical phenomena, random walks in finance and physics, physics-inspired methods for time-series analysis, multiscale problems in the analysis of time series, early-warning indicators, discrete scale invariance and log-periodic power laws)*

Initial competences

Basic course in Statistical Physics ; Basic course in programming for Engineers & Scientists (Python or comparable computer language)

Final competences

1 To grasp the fundamental statistical theories underlying the dynamics of complex systems consisting of many interacting units.
2 To gain familiarity with advanced simulation techniques based on modern physical theories.
3 To develop the skills to apply these simulation techniques within a variety of engineering disciplines.
4 To gain familiarity with the present quantitative understanding of how complex systems respond to external changes.
5 To gain a fundamental understanding of phases and phase transitions (sudden changes) in complex systems.

Conditions for credit contract

Access to this course unit via a credit contract is determined after successful competences assessment

Conditions for exam contract

This course unit cannot be taken via an exam contract

Teaching methods

Seminar, Lecture, Independent work

Study material

Type: Handbook

Name: Chapters from Several Books
Indicative price: Free or paid by faculty
Optional: no
Language : English
Online Available : Yes
Available in the Library : Yes

Type: Slides

Name: Presentations that accompany the theory classes.
Indicative price: Free or paid by faculty
Optional: no
Language : English
Available on Ufora : Yes

Type: Handouts

Name: Notes with exercises and model solutions that accompany the problem sessions
Indicative price: Free or paid by faculty
Optional: no
Language : English
Available on Ufora : Yes

References

1 Kim Christensen and Nicholas R. Moloney: "Complexity and Criticality" (Imperial College Press, 2005)
2 Harvey Gould and Jan Tobochnik: "Statistical and Thermal Physics (Second Edition)" (Princeton University Press, 2021)
3 James P. Sethna, "Statistical Physics: Entropy, Order Parameters and Complexity (Second Edition)" (Oxford University Physics, 2021)
4 Ricard V. Solé, "Phase Transitions" (Princeton University Press, 2011)
5 Stefan Thurner, Rudolf Hanel, Peter Klimek, "The Theory of Complex Systems" (Oxford University Physics, 2018)
6 Hendrik Jeldtoft Jensen, "Complexity Science: The Study of Emergence" (Cambridge Unviersity Press, 2023)

Course content-related study coaching

The instructor(s) can be contacted after the lectures, or by appointment. Interactive support via Ufora. The lecturer offers the possibility to discuss the course material with individual or small groups of students. The university's electronic learning environment is employed to discuss the course material with the students and to draw their attention to current research advances in complexity science.

Assessment moments

end-of-term assessment

Examination methods in case of periodic assessment during the first examination period

Oral assessment, Written assessment open-book

Examination methods in case of periodic assessment during the second examination period

Oral assessment, Written assessment open-book

Examination methods in case of permanent assessment

Possibilities of retake in case of permanent assessment

not applicable

Extra information on the examination methods

The theory part of the course is evaluated during the oral exam. The written exam consists of problems.

Calculation of the examination mark

- open-book written exam counts for 40% of the total mark
- oral exam counts for 60% of the total mark