SYLLABUS

Methods of Stochastic Simulations in Statistical Physics. Interdisciplinary Applications

University year 2025/2026

1. Information regarding the programme

1.1. Higher education institution	Babeș-Bolyai University
1.2. Faculty	Faculty of Physics
1.3. Department	Department of Physics – Hungarian Line of Study
1.4. Field of study	Physics
1.5. Study cycle	Master
1.6. Study programme/Qualification	Computational Physics
1.7. Form of education	

2. Information regarding the discipline

2.1. Name of the discipline	**Methods of Stochastic Simulations in Statistical Physics. Interdisciplinary Applications**					Discipline code	**FME3402**
2.2. Course coordinator					conf. dr. Járai-Szabó Ferenc lect. dr. Tyukodi Botond		
2.3. Laboratory coordinator					conf. dr. Járai-Szabó Ferenc lect. dr. Tyukodi Botond		
2.4. Year of study	1	2.5. Semester	2	2.6. Type of evaluation	E	2.7. Discipline regime	DA

3. Total estimated time (hours/semester of didactic activities)

3.1. Hours per week	**5**	of which: 3.2 course	**3**	3.3 Laboratory	**2**
3.4. Total hours in the curriculum	70	of which: 3.5 course	**42**	3.6 Laboratory	**28**
Time allotment for individual study (ID) and self-study activities (SA)					**hours**
Learning using manual, course support, bibliography, course notes (SA)					14
Additional documentation (in libraries, on electronic platforms, field documentation)					14
Preparation for seminars/labs, homework, papers, portfolios and essays					42
Tutorship					5
Evaluations					5
Other activities:					0
3.7. Total individual study hours	**80**				
3.8. Total hours per semester	**150**				
3.9. Number of ECTS credits	**6**				

4. Prerequisites (if necessary)

4.1. curriculum	
4.2. competencies	Basic programming skills, basic physics knowledge, logical thinking, interdisciplinary thinking, English communication skills

5. Conditions (if necessary)

5.1. for the course	video projector, whiteboard
5.2. for the seminar /lab activities	computers with Linux or Windows operating systems, Video projector

6.1. Specific competencies acquired [1]

Professional/essential competencies	• C1. Capacities for analyzing and synthetizing physical data, capacities for modelling complex phenomena. • C2. Working and mastering with software packages for analyzing and processing experimental data. Using C, Python and Mathematica software for modelling complex phenomena. Capacities for using information technologies in describing complex phenomena from physics, biology, chemistry and social sciences. Advanced programming techniques. • C3. Trans- and Interdisciplinary thinking. • C4. Planning and Performing computer experiments for validating physical models. Abilities for making high performance computations in physics. Capacities for writing computer codes and running them on modern supercomputers. • C5. Communicating efficiently modern scientific ideas. Presenting in a professional manner results of a research or scientific projects. Capacities for writing scientific publications, to interact and have a scientific debate with Editors and Referees. Capacities for arguing and defending scientific views and ideas
Transversal competencies	• CT1. To deal with professional duties efficiently and in a responsible manner, keeping in mind the laws and scientific ethics. Being responsible for the published scientific results and taking all actions fot their proper use. • CT2. Working in an Interdisciplinary environment respecting the professional hierarchy. Having initiative, new ideas and approaches to classical problems. Promoting the dialogue, cooperation and positive attitude in a group. Respecting multicultural environment and helping the others. • CT3. Efficient use of information technology tools and presentation methods in English. Learning and applying auto evaluation methods, f or keeping the professional training up to date, in agreement with the demands of the market.

6.2. Learning outcomes

Knowledge	The student knows the fundamental principles of stochastic processes, statistical mechanics, and critical phenomena, including random walks, Markov chains, and phase transitions. [C1] The student knows the theoretical basis of advanced Monte Carlo algorithms, numerical integration, and optimization techniques used in modern computational physics. [C1 C4] The student knows how to apply these stochastic modeling concepts across diverse disciplines, connecting microscopic phenomena to macroscopic laws in general physics, high-energy physics, and complex systems. [C2 C3]
Skills	The student is able to develop, optimize, and execute computer codes (using Python, C, or Mathematica) to simulate complex physical phenomena and perform high-performance computations. [C2 C4] The student is able to design computer experiments, analyze simulated data, and validate physical models using advanced statistical techniques and error estimation. [C1 C4] The student is able to efficiently communicate scientific ideas in English, presenting research results professionally and structuring findings for scientific publications and debates. [C5 CT3]
Responsibility and autonomy:	The student has the ability to work independently to obtain valid and reliable scientific results, taking full ethical responsibility for the accuracy and proper use of published computational data. [CT1] The student has the ability to work independently to obtain successful outcomes within interdisciplinary and multicultural research teams, demonstrating initiative, promoting positive dialogue, and respecting professional hierarchies. [C3 CT2] The student has the ability to work independently to obtain up-to-date professional training, actively using self-evaluation methods to adapt their skills to the evolving demands of the scientific community and job market. [CT3]

[1] One can choose either competences or learning outcomes, or both. If only one option is chosen, the row related to the other option will be deleted, and the kept one will be numbered 6.

7. Objectives of the discipline (outcome of the acquired competencies)

7.1 General objective of the discipline	• The primary objective of this course is to equip students with the theoretical foundations and advanced computational skills necessary to model, simulate, and analyze complex stochastic phenomena. By treating stochastic methods as a universal scientific language, the course aims to bridge the gap between microscopic probabilistic interactions and macroscopic physical laws, preparing students to tackle advanced research problems in Computational Physics, High-Energy Physics (HEP), and Interdisciplinary Complex Systems.
7.2 Specific objective of the discipline	• **Theoretical Foundations:** To provide a deep understanding of statistical mechanics, critical phenomena, and stochastic processes (such as Random Walks, Markov Chains, and the Detailed Balance condition) and their role in driving phase transitions. • **Algorithmic Mastery:** To teach the physical justifications and mathematical mechanics behind state-of-the-art Monte Carlo simulation algorithms, including Metropolis-Hastings, Glauber Dynamics, Kinetic Monte Carlo (BKL), and Cluster update algorithms (Swendsen-Wang, Wolff). • **Computational Implementation:** To develop students' abilities to write, optimize, and execute high-performance computer codes (using Python, C, or Mathematica) capable of simulating complex systems like the 2D Ising model, colloidal suspensions, and detector scattering events. • **Data Analysis & Validation:** To train students in designing computer experiments, performing phase space integration (Importance Sampling), addressing algorithmic challenges like Critical Slowing Down, and utilizing data resampling techniques for rigorous error estimation. • **Interdisciplinary Application:** To demonstrate the transdisciplinary power of stochastic simulations by applying the same fundamental algorithms to diverse scenarios, including heat bath modeling (Langevin dynamics), particle trajectory tracking in HEP detectors, and sociological phase transitions (the "Rat" system). • **Professional & Scientific Communication:** To cultivate the skills required to interpret simulation results, present scientific findings efficiently in English, and format data for high-level academic publications and peer-reviewed debates while adhering to strict scientific ethics.

8. Content

8.1 Course	Teaching methods	Remarks
Introduction to Stochastic Methods: Random walks, deterministic vs. stochastic modeling, and interdisciplinary applications (General Physics, HEP, and Complex Systems). **Statistical Physics Foundations:** Markov chains, detailed balance, and critical phenomena (phase transitions). **Random Numbers & Integration:** PRNGs, sampling distributions, and Monte Carlo/Importance Sampling. **Brownian Dynamics:** The Langevin equation, Fokker-Planck equation, and thermal noise modeling. **The Ising Model:** Hamiltonians, 1D exact solutions, and Mean Field Theory.	The teaching methodology combines interactive, multimedia-supported lectures with whiteboard calculations and code demonstrations.	

Metropolis & Glauber Dynamics: Single-spin flip algorithms, ergodicity, autocorrelation, and data resampling (Jackknife/Bootstrap). **Markov-State Models (MSMs):** Discretizing phase space, transition matrices, spectral analysis, and applications for non-equilibrium systems. **Kinetic Monte Carlo:** The Bortz-Kalos-Lebowitz (BKL) algorithm for low-temperature simulations. **Cluster Algorithms:** Overcoming critical slowing down using Swendsen-Wang and Wolff algorithms. **Advanced Ensembles:** Histogram reweighting (Ferrenberg-Swendsen) and Microcanonical MC (Creutz Demon). **Global Optimization:** Optimization landscapes and Simulated Annealing.		
Bibliography 1. Z. Neda: Stochastic simulations in physics with interdisciplinary applications, http://www.phys.ubbcluj.ro/~zneda/edu/mc.htm 2. H. Gould and J. Tobochnik Introduction to Computer Simulation Methods and applications in physics (Addison Wesley, 1996). 3. F. Bagnoli: Introduction to Cellular Automata (cond-mat/9810012; arxiv.org, 1998) 4. David Landau and Kurt Binder: A guide to Monte Carlo Simulations in Statistical Physics, Cambridge Univ. Press, 2004		
8.2 Laboratory	Teaching methods	Remarks
The laboratory activities consist of hands-on, problem-based coding sessions designed to implement and explore the stochastic algorithms discussed during the lectures. Using programming languages such as Python or C, students will develop efficient simulation codes to solve specific computational physics problems—ranging from simple random walks and Monte Carlo integration to complex phase transitions and optimization landscapes. These practical sessions emphasize algorithmic implementation, data analysis, the validation of physical models against theoretical expectations, and the synthesis of results into professional scientific reports.	The teaching methods for the laboratory are centered on problem-based learning and guided discovery. Sessions are practical guided through laboratory worksheets, and on request the instructor provides individualized, real-time feedback on algorithmic implementation, debugging, and data interpretation.	
Bibliography similar to course bibliography.		

9. Corroborating the content of the discipline with the expectations of the epistemic community, professional associations and representative employers within the field of the program

- The syllabus and the studied material agree with similar courses from other universities in Romania and abroad. For helping the integration with the demands of the work-force market, the syllabus was harmonized with the demands of the pre-university and university educations, of those of research institutes and the business sector.

10. Evaluation

Activity type	10.1 Evaluation criteria	10.2 Evaluation methods	10.3 Percentage of final grade
10.4 Course	The student's comprehension of the theoretical foundations of statistical physics and stochastic processes. The ability to explain algorithmic logic (e.g., Metropolis, Langevin, Monte Carlo integration) and correctly interpret the physical meaning behind computational models.	A face-to-face oral examination during the official examination period, consisting of theoretical questions and a conceptual discussion of the course material.	40%
10.5 Laboratory	The functionality, efficiency, and correctness of the submitted simulation codes (Python/C). The accuracy of the extracted physical data, the proper application of statistical error estimation, and the clarity, structure, and scientific reasoning presented in the short PDF reports.	Continuous assessment of the code files and laboratory reports submitted to the Moodle e-learning platform across the semester.	30%
	The student's autonomy in modeling a complex physical phenomenon using advanced stochastic methods. The quality of the visual data presentation, the clarity of scientific communication, and the ability to professionally argue and defend the results during a scientific debate.	An oral presentation of the final research project to the class and instructor, followed by a Q&A session.	30%

10.6 Minimum standard of performance

To successfully pass this discipline (achieving a minimum final grade of 5 out of 10), the student must demonstrate a fundamental understanding of stochastic methods and basic computational competency. Specifically, the student must meet the following minimum criteria:

- Theoretical Knowledge (Oral Exam): Demonstrate a basic understanding of core concepts such as random walks, the Monte Carlo method, and phase transitions, correctly answering at least half of the fundamental theoretical questions (minimum passing grade 4.50).
- Laboratory Activity: Submit functional (even if unoptimized) simulation codes and basic PDF reports for at least 50% of the assigned laboratory tasks (minimum passing grade 4.50).
- Project: Deliver a functional, basic computational physics simulation and present the results in a coherent, understandable manner (minimum passing grade 4.50).
- Overall Grade: Achieve a final weighted average score of at least 5.00 (Oral Exam x 0.4 + Lab x 0.3 + Project x 0.3 $\geq$ 4.50).

11. Labels SDG (Sustainable Development Goals)

	General label for Sustainable Development							
4 QUALITY EDUCATION	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE							

Date:
25.04.2026.

Course coordinator

Laboratory coordinator

Date of approval:
25.04.2026.

Head of department