

## SYLLABUS

### *Introduction to the theory of complex systems*

University year 2025-2026

#### 1. Information regarding the programme

1.1. Higher education institution	Babeş-Bolyai University
1.2. Faculty	Faculty of Psychology and Educational Sciences
1.3. Department	Department of Psychology
1.4. Field of study	Psychology - Cognitive Sciences
1.5. Study cycle	Bachelor level
1.6. Study programme/Qualification	Psychologist
1.7. Form of education	Full-time

#### 2. Information regarding the discipline

2.1. Name of the discipline	Introduction to the theory of complex systems			Discipline code	<b>PLE1320</b>		
2.2. Course coordinator	Dr. Habil. CS. I. Maria Ercsey-Ravasz						
2.3. Seminar coordinator	Dr. CS. III Istvan-Ferenc Toth						
2.4. Year of study	2	2.5. Semester	3	2.6. Type of evaluation	E	2.7. Discipline regime	0

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

3.1. Hours per week	3	of which: 3.2 course	2	3.3 seminar/laboratory	1
3.4. Total hours in the curriculum		of which: 3.5 course		3.6 seminar/laborator	
<b>Time allotment for individual study (ID) and self-study activities (SA)</b>					<b>hours</b>
Learning using manual, course support, bibliography, course notes (SA)					10
Additional documentation (in libraries, on electronic platforms, field documentation)					4
Preparation for seminars/labs, homework, papers, portfolios and essays					16
Tutorship					14
Evaluations					14
Other activities:					
<b>3.7. Total individual study hours</b>			<b>58</b>		
<b>3.8. Total hours per semester</b>			<b>100</b>		
<b>3.9. Number of ECTS credits</b>			<b>4</b>		

#### 4. Prerequisites (if necessary)

4.1. curriculum	<ul style="list-style-type: none"> <li>- high school level mathematics,</li> <li>- basic computer skills</li> <li>- basic knowledges in natural sciences</li> </ul>
4.2. competencies	<ul style="list-style-type: none"> <li>- logical thinking,</li> <li>- laboratories interdisciplinary thinking</li> <li>- communication abilities in English</li> <li>- active participation at the courses and seminars</li> </ul>

#### 5. Conditions (if necessary)

5.1. for the course	Classroom with at least 180 seats, computer and video projector / Online course conducted through the ZOOM platform.
---------------------	--

5.2. for the seminar /lab activities	Room with at least 50 seats, computer and video projector / Online seminar conducted through the ZOOM platform
--------------------------------------	--

## 6. Specific competencies acquired <sup>1</sup>

<b>Professional/essential competencies</b>	<p><b>Knowledge and understanding</b></p> <ul style="list-style-type: none"> <li>- trans- and interdisciplinary thinking</li> <li>- view on the complexity of our physical and social world</li> <li>- understanding deterministic and probabilistic modelling</li> <li>- understanding the principles governing modern natural sciences</li> <li>- critical thinking on the limitations offered by predictive models</li> <li>- a glimpse in actual challenges in modern physics, biology, economics, sociology, etc...</li> </ul> <p><b>Explanation and interpretation</b></p> <ul style="list-style-type: none"> <li>- science communication skills</li> <li>- science popularization skills and methods</li> <li>- interpretation of scientific results from various fields of modern science</li> <li>- skills for scientific dialog involving various fields of sciences</li> </ul> <p><b>Instrumental - applicative</b></p> <ul style="list-style-type: none"> <li>- use of modern presentation techniques</li> <li>- use of computational programs targeting complex systems</li> <li>- use of some basic experimental devices</li> </ul> <p><b>Attitude</b></p> <ul style="list-style-type: none"> <li>- working in an interdisciplinary environment</li> <li>- openness</li> </ul>
<b>Transversal competencies</b>	<ul style="list-style-type: none"> <li>• 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 for their proper use.</li> <li>• 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.</li> <li>• CT3. Efficient use of information technology tools and presentation methods in English. Learning and applying auto evaluation methods, for keeping the professional training up to date, in agreement with the demands of the modern societies.</li> </ul>

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

<b>7.1 General objective of the discipline</b>	<ul style="list-style-type: none"> <li>• To offer an introduction on a science popularization level to selected problems concerning complex systems. To exemplify modeling and analytical methods in describing these systems.</li> </ul>
<b>7.2 Specific objective of the discipline</b>	<ul style="list-style-type: none"> <li>• understanding the notion of complexity</li> <li>• to discuss some specific complex system on science popularization level</li> <li>• to discuss modelling methods used in complex systems</li> <li>• to present and discuss some important achievements in modern sciences</li> <li>• to understand the probabilistic nature of some specific models</li> <li>• to discuss universalities and models with universal applicability</li> </ul>

## 8. Content

8.1 Course	Teaching methods	Remarks
<p><b>1. Complexity versus simplicity</b></p> <p>What is complexity, what are complex systems? Examples of simple and complex systems. Chaos and Stochastic phenomena. The notion</p>	Lecture, demonstrative examples, synthesis of knowledge, guided discovery	[1], [7]

<sup>1</sup> 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.

<p>of probability. From deterministic to probabilistic description and modelling. Systems with few and many bodies. Measures of complexity.</p> <p><b>Keywords:</b> complex systems, chaotic systems, probabilistic prediction</p>		
<p><b>2. Complexity in patterns. Geometrical complexity.</b></p> <p>Simple and complex geometrical patterns. Julia and Mandelbrot sets. Fractals in mathematics. Examples: the Koch curve, Cantor sets, Sierpinski gasket. Fractals in nature. General models for pattern formation. Characterization of fractal patterns.</p> <p><b>Keywords:</b> iterations in mathematics, fractals, pattern formation</p>	<p>Lecture, demonstrative examples, computer exercise, synthesis of knowledge, guided discovery, projection of movies</p>	<p>[4],[9]</p>
<p><b>3. Complex networks I.</b></p> <p>Why networks? The network backbone of a complex systems. Graphs and networks. Simple graphs and networks. Basic properties and measures for characterizing networks. Random networks. Statistical description method. The Erdos-Renyi network. Examples from physics, biology and sociology.</p> <p><b>Keywords:</b> graphs, complex networks, Erdos-Renyi graph.</p>	<p>Lecture, demonstrative examples, computer exercise, synthesis of knowledge, guided discovery</p>	
<p><b>4. Complex networks II.</b></p> <p>Scale-free and small-world networks. Examples and simple models. How to study a complex system from a network-science viewpoint. Robustness of a network. Computational studies on networks. Social-networks. Examples, computational tools.</p> <p><b>Keywords:</b> scale-free networks, small-world networks, basic network models</p>	<p>Lecture, demonstrative examples, computer exercise, synthesis of knowledge, guided discovery</p>	
<p><b>5. Network neuroscience</b></p> <p>Structural brain networks on micro-, meso, macro-scale. Characterizing, modeling these networks. Physical and geometrical properties. The exponential distance rule. The EDR model. Functional brain networks, definition, methods of analysis.</p>	<p>Lecture, demonstrative examples, computer exercise, synthesis of knowledge, guided discovery</p>	
<p><b>6. Chaotic systems</b></p> <p>What is chaos and what is not chaos. Difference between chaotic and stochastic phenomena.</p>	<p>Lecture, demonstrative examples, computer exercise, synthesis of knowledge, guided discovery</p>	<p>[2],[7]</p>

<p>Simple examples from physics. Discrete time and continuous time dynamics. Phase-portrait of a dynamical system, fixpoints, attractors. The route to chaos. The chaotic attractor. Chaos in physical systems. Predictability limit in chaotic systems.</p> <p><b>Keywords:</b> dynamical systems, chaos, attractors, predictability</p>		
<p><b>7. Stochastic systems I.</b></p> <p>Difference between stochastic and chaotic systems. What is randomness. The source of true randomness. The mathematical notion of probability, interpreting probability and probability distributions. Brownian motion and random walks. The central limit theorem. Galton table and normal distribution. Scaling and non-Markovian random walks.</p> <p><b>Keywords:</b> stochastic phenomena, Brownian motion, random walks, normal distribution</p>	<p>Lecture, demonstrative examples, computer exercise, synthesis of knowledge, guided discovery</p>	<p>[6],[10]</p>
<p><b>8. Stochastic systems II.</b></p> <p>Random processes in science. Characteristic distributions. Examples from physics, biology, economics, sociology. Power-law tailed and exponential distributions. Master-equation approach. Random numbers. Monte Carlo simulations of stochastic phenomena.</p> <p><b>Keywords:</b> stochastic phenomena, scale-free distributions, random numbers, Monte Carlo methods</p>	<p>Lecture, demonstrative examples, computer exercise, synthesis of knowledge, guided discovery</p>	<p>[6],[10]</p>
<p><b>9. The importance of models and modelling.</b></p> <p>What is a model? Simple versus complex models. Examples from physics, biology and economics. The importance of universalities and simple models capturing universalities. Basic steps in constructing a model. Model parameters and how to study a model. How to improve models. Simple models for complexity. From deterministic models to stochastic models. Examples.</p> <p><b>Keywords:</b> universalities, analytic and computational models, stochastic modelling</p>	<p>Lecture, demonstrative example, synthesis of knowledge, guided discovery</p>	<p>[1]</p>
<p><b>10. Many particle systems</b></p> <p>The statistical description method. Statistical laws in many particle systems. Ensembles. Interactive and non-interactive particle systems. Phase-transitions. Critical behavior in the vicinity of phase-transition. Universalities. Phase transitions in physical and non-physical</p>	<p>Lecture, demonstrative examples, computer exercise, synthesis of knowledge, guided discovery</p>	<p>[6]</p>

<p>systems. The Ising model and its interdisciplinary applications.</p> <p><b>Keywords:</b> statistical ensembles, phase-transition, critical behavior, Ising model</p>		
<p><b>11. Collective behavior I.</b></p> <p>What is collective behavior? Examples from physics, biology and sociology. Emergence.</p> <p>Spontaneous synchronization. Examples. Playing with metronomes. The Kuramoto model. Phase transition in the Kuramoto model. The millennium bridge story, and the story of rhythmic applause. Beyond the Kuramoto model. Chimera states...</p> <p><b>Keywords:</b> spontaneous synchronization, Kuramoto model, emergence, chimera states</p>	<p>Lecture, demonstrative examples, computer exercise, synthesis of knowledge, guided discovery</p>	<p>[5]</p>
<p><b>12. Collective behavior II.</b></p> <p>Spatio-temporal patterns from self-organized phenomena. Fracture and fragmentation. Universalities and models. Swarming and flocking. Pedestrian and car-traffic. Experiments, current challenges, Basic models and results. The Vicsek model.</p> <p><b>Keywords:</b> flocking, traffic models, Vicsek model, fracture, fragmentation</p>	<p>Lecture, demonstrative examples, computer exercise, synthesis of knowledge, guided discovery</p>	<p>[5]</p>
<p><b>13. Self-organized criticality</b></p> <p>What is self-organized criticality? Examples from physics. The universality of the <math>1/f</math> noise. Earthquakes and avalanches. Universalities in Earthquake events: the Guttenberg-Richer and Omori law. The sand-pile model. The spring-block model for earthquakes.</p> <p><b>Keywords:</b>, SOC (self-organized criticality), avalanches, <math>1/f</math> noise, SOC models.</p>	<p>Lecture, demonstrative examples, computer exercise, synthesis of knowledge, guided discovery</p>	<p>[1],[4]</p>
<p><b>14. Algorithmic complexity</b></p> <p>Basics of mathematical complexity. What is hard and easy computationally. Polinomial and non-polinomial problems on computers. NP complete and NP hard problems. Examples: factorization, Hamiltonian cycle in graphs, graph coloring, traveling-salesman problem, spin-glasses, protein-folding, correlation-clustering, etc... Challenges in solving</p>	<p>Lecture, demonstrative examples, computer exercise, synthesis of knowledge, guided discovery</p>	<p>[1]</p>

<p>computationally complex problems. Computational methods to tackle with mathematical complexity. Quantum computing.</p> <p><b>Keywords:</b> P and NP problems. NP hard and NP complex problems, mathematical complexity, quantum computing</p>		
<p>Bibliography</p> <p>[1] M. Mitchell; <i>Complexity: a Guided Tour</i> (Oxford University Press, 2011)</p> <p>[2] Claudius Gros; <i>Complex and Adaptive Dynamical Systems, A Primer</i> (Springer, 2018)</p> <p>[3] A.L. Barabási, <i>Linked</i> (Basic Books, 2014)</p> <p>[4] B. Mandelbrot: <i>The fractal geometry of Nature</i> (Times Books, 1982)</p> <p>[5] S. H. Strogatz, <i>Sync: How Order Emerges From Chaos In the Universe, Nature, and Daily Life</i> (Hyperion, New York, 2004)</p> <p>[6] H. Gould and J. Tobochnik <i>Introduction to Computer Simulation Methods and applications in physics</i> (Addison-Wesley, 1996).</p> <p><b>Optional references:</b></p> <p>[7] M. Mitchell Waldrop; <i>Complexity: The emerging Science at the edge of order and chaos</i> (Simon &amp; Schuster, 1993)</p> <p>[8] A.L. Barabasi, <i>Network Science</i> (Cambridge University Press, 2016)</p> <p>[9] T. Vicsek: "<i>Fractal Growth Phenomena</i>" (World Scientific, Singapore, New Jersey, 1989)</p> <p>[10] A. MacKinnon: <i>Computational Physics online course</i> (<a href="http://b.sst.ph.ic.ac.uk/~angus/Lectures/compphys/compphys.html">http://b.sst.ph.ic.ac.uk/~angus/Lectures/compphys/compphys.html</a>)</p>		
8.2 Seminar / laboratory	Teaching methods	Remarks
<p><b>1. Mathematical foundations</b></p> <p>Functions, derivative of a function, Taylor series, complex numbers and their operations. Elements of descriptive statistics: mean, median, standard deviation. Correlation and regression. Basic probability rules.</p> <p><b>Keywords:</b> derivative, complex numbers, statistics, probability</p>	<p>Exposure, conversation, problem solving, using these concepts in a programming environment</p>	
<p><b>2. Probability distributions</b></p> <p>Discrete and continuous distributions. Poissonian, binomial, normal, exponential, distributions. Probability distribution and density functions</p> <p><b>Keywords:</b> Distribution function, Probability density functions</p>	<p>Presentation, knowledge synthesis, conceptual clarification, practical activities</p>	
<p><b>3. Playing with fractals</b></p>	<p>Presentation, knowledge synthesis, conceptual clarification, group activities,</p>	

<p>The Julia and Mandelbrot set. Calculating fractal dimensions.</p> <p><b>Keywords:</b> Fractals</p>	<p>guided discovery, practical activities, computer exercises</p>	
<p><b>4. Complex networks I.</b></p> <p>Exercises on simple graphs. Generating and illustrating simple graphs and networks.</p> <p><b>Keywords:</b> graphs, networks</p>	<p>Presentation, knowledge synthesis, conceptual clarification, group activities, guided discovery, practical activities, computer exercises</p>	
<p><b>5. Complex networks II.</b></p> <p>The adjacency matrix. Illustrating graphs. Calculating graphs and network properties on simple graphs.</p> <p><b>Keywords:</b> degree distribution, clustering coefficient, network diameter</p>	<p>Presentation, knowledge synthesis, conceptual clarification, group activities, guided discovery, practical activities, computer exercises</p>	
<p><b>6. Network neuroscience</b></p> <p>Calculating network measures of functional brain networks. The EDR model.</p> <p><b>Keywords:</b> centrality measures, EDR model</p>	<p>Presentation, knowledge synthesis, conceptual clarification, group activities, guided discovery, practical activities, computer exercises</p>	
<p><b>7. Chaotic systems</b></p> <p>Exercises with dynamical systems. The logistic map. Phase-portraits on the computer. Chaotic attractors on computer.</p> <p><b>Keywords:</b> chaos, attractors, exercises with simple discrete dynamics.</p>	<p>Presentation, knowledge synthesis, conceptual clarification, group activities, Guided discovery, practical activities, computer exercises</p>	
<p><b>8. Stochastic systems I.</b></p> <p>Exercises with random walks. Studying the Galton table.</p> <p><b>Keywords:</b> random walks, Galton table</p>	<p>Presentation, knowledge synthesis, conceptual clarification, group activities, guided discovery, conversation, computer exercises</p>	
<p><b>9. Stochastic systems II.</b></p> <p>Generating random numbers. Example for a simple Monte Carlo simulation for random walks.</p> <p><b>Keywords:</b> random number, Monte Carlo method</p>	<p>Presentation, knowledge synthesis, conceptual clarification, group activities, guided discovery, practical activities, computer exercises</p>	
<p><b>10. Many particle systems</b></p> <p>Molecular dynamics simulations of many particle systems. A funny problem... Computer exercise. Phase-transitions simulation on the computer.</p>	<p>Presentation, knowledge synthesis, conceptual clarification, group activities, guided discovery, conversation, computer exercises</p>	

<p><b>Keywords:</b> molecular dynamics, computer simulation exercise.</p>		
<p><b>11. Collective behavior I.</b></p> <p>Simulating the Kuramoto model. Investigating the phase-transition in the Kuramoto model with computers.</p> <p><b>Keywords:</b> Kuramoto model, metronomes, synchronization</p>	<p>Presentation, knowledge synthesis, conceptual clarification, group activities, guided discovery, conversation, computer exercises</p>	
<p><b>12. Collective behavior II.</b></p> <p>Exercises with computational traffic and pedestrian models. Exercises with the Vicsek model.</p> <p><b>Keywords:</b> traffic models, pedestrian model, Vicsek model</p>	<p>Presentation, knowledge synthesis, conceptual clarification, group activities, guided discovery, conversation, computer exercises</p>	
<p><b>13. Self organized criticality (SOC)</b></p> <p>Exercises with the sand-pile model and Burridge-Knopoff model for Earthquakes.</p> <p><b>Keywords:</b> sand-pile model, Burridge-Knopoff model</p>	<p>Presentation, knowledge synthesis, conceptual clarification, group activities, guided discovery, conversation</p>	
<p><b>14. Algorithmic complexity</b></p> <p>Comparing and visualizing the running times for polynomial and non-polynomial problems on the computer.</p> <p><b>Keywords:</b> running time, polynomial and non-polynomial complexity</p>	<p>Presentation, knowledge synthesis, conceptual clarification, group activities, guided discovery, conversation, computer exercises</p>	
<p>Bibliography</p> <p><b>Mandatory references:</b>  M. Mitchell; <i>Complexity: a Guided Tour</i> (Oxford University Press, 2011)</p> <p>Claudius Gros; <i>Complex and Adaptive Dynamical Systems, A Primer</i> (Springer, 2018)</p> <p>H. Gould and J. Tobochnik <i>Introduction to Computer Simulation Methods and applications in physics</i> (Addison-Wesley, 1996).</p> <p><b>Optional references:</b>  M. Mitchell Waldrop; <i>Complexity: The emerging Science at the edge of order and chaos</i> (Simon &amp; Schuster, 1993)</p> <p>A.L. Barabasi, <i>Network Science</i> (Cambridge University Press, 2016)</p>		

**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 proposed lecture and seminar offer central topics in fundamental and applied research in the fields of cognitive sciences, and their approach is based on the most recent results found in the literature. The course also offers state of the art research skills that are transferable to any scientific and applied field of knowledge.

## 10. Evaluation

Activity type	10.1 Evaluation criteria	10.2 Evaluation methods	10.3 Percentage of final grade
10.4 Course	Assimilation of the course material	written exam	70%
	Scientific arguing, presentation, willingness for debate and logical thinking		
10.5 Seminar/laboratory	Participation in group activities, participation in debates	Seminar activity	30%
10.6 Minimum standard of performance			
<ul style="list-style-type: none"> <li>• score of minimum 5 (45%)</li> </ul> <p><b>The final grade consists of:</b></p> <ol style="list-style-type: none"> <li>a. score obtained in the written exam in proportion of 70%</li> <li>b. seminar activity in proportion of 30%</li> </ol>			

## 11. Labels ODD (Sustainable Development Goals)<sup>2</sup>

Not applicable

<sup>2</sup> Keep only the labels that, according to the [Procedure for applying ODD labels in the academic process](#), suit the discipline and delete the others, including the general one for *Sustainable Development* – if not applicable. If no label describes the discipline, delete them all and write „*Not applicable.*”.

Date:  
23.09.2025

Signature of course coordinator

Maria Ercsey-Ravasz

Signature of seminar coordinator

Istvan-Ferenc Toth

Date of approval:

...

Signature of the head of department

.....