2EL1110 – Dynamical systems in neuroscience

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Department: DÉPARTEMENT AUTOMATIQUE
Language of instruction: ANGLAIS
Campus: CAMPUS DE PARIS - SACLAY
Workload (HEE): 60
On-site hours (HPE): 35,00
Elective Category : Engineering Sciences
Advanced level : Yes

Description

This course constitutes an introduction to tools for the analysis of dynamical processes involved in brain functioning. Despite their huge complexity, brain functions are indeed based on elementary dynamics, some of which can be apprehended by a mathematical approach. Mastering these techniques is fundamental to progress in our understanding of brain functioning, to optimize instrumentation for brain activity measurements (brain imaging, electrophysiological recordings…), to improve brain-machine interfaces, to build up neuro-inspired computational units, and to understand the mechanisms involved in some brain diseases and thus improve their treatment.

Quarter number

SG6

Prerequisites (in terms of CS courses)

- SG1 : Information systems and programming
- SG1-ST2-SG3 : Convergence, integration, probability, partial differential equations
- ST2 : Modelling
- ST4 : Signal processing
- ST5 : Control theory

Syllabus

Chapter 1: Fundamentals in physiology and brain functions (CM: 6h)

This first chapter introduces the physiological bases of neuronal activity. It describes the elementary principles involved in the generation of an action potential and in the communication between

neurons (soma, axon, dendrite, synapse, ion channels, rest potential), as well as synaptic plasticity and homeostatic regulation mechanisms. It describes the physical and biological principles that come into play in these behaviors. It finally presents the main brain functions (memory, motor tasks, olfaction, and vision) and their alteration in pathological conditions.

Chapter 2: Measurement and actuation of brain activity (CM: 3h)
This second chapter presents different techniques to measure brain activity, including electrophysiological techniques (patch-clamp, multi-unit recordings, LFP, EEG, MEG) and brain imaging (MRI, 2-photon). It also describes technological ways to influence brain activity, including electrical stimulation and optogenetics.

Chapter 3: Brain-machine interfaces (CM: 4.5h)
This sixth chapter addresses the development of brain-machine interfaces, also known as neuroprostheses. These devices aim at restoring the autonomy of amputated or quadriplegic patients. Their implementation in animals or humans also provides knowledge on the functioning and learning of natural sensory-motor loops. This chapter details the needed elements for such interfaces: neuronal activity recording (whether invasive or not), signal processing, motor control, and sensory feedback from the prosthesis to the brain. It also describes the plasticity mechanisms on which these interfaces can rely to optimize learning.

Chapter 4: Mathematical models of neurons (CM: 3h)
This chapter presents well-known neuron models. It introduces conductance-based models through the famous Hodgkin-Huxley model and underlines its electronic analogy. It then presents simplified models, such as integrate & fire or FitzHug-Nagumo models, as well as simple models of synapses and neuronal plasticity. Numerical simulation of these models is also introduced.

Chapter 5: Analysis of neuron models (CM: 6h, TP: 3h)
This chapter present mathematical tools to study neuronal behavior. It introduces the notion of phase diagram and bifurcation. These notions are first given for one-dimensional systems, and then for planar systems. The chapter establishes a link between these bifurcations and the qualitative behavior of the neuron. A lab session on Matlab-Simulink aims at implementing a conductance-based model of a neuron and to predict its response thanks to the introduced theoretical tools.

Chapter 6: Neuronal populations (CM: 3h, TP: 3h)
This chapter addresses the dynamics of a whole population of neurons or a cerebral structure. It presents simplified models of the activity of a

population, such as the Wilson-Cowan model or neural fields. It shows how to predict the behavior of such models by stability or bifurcation analysis. A lab session on Matlab-Simulink will aim at studying the binocular rivalry phenomenon through a simple neuronal population model.

Conference: Example of a start-up creation (1.5h)
A conference by the co-funder and scientific manager of start-up Dreem (Rhythm) concludes this course by presenting recent industrial innovations (non-invasive measurement of brain activity, pattern recognition in electrophysiological data, …) as well as opportunities given by neuroscience for industry and entrepreneurship.

Class components (lecture, labs, etc.)
CM, TD, TP, homework.

Grading
Evaluation will be made based on a written exam without documents (2h) at the end of the course and on the written reports of the two lab sessions. The following weights are envisioned: 60% for the written exam and 20% for each lab session report. Any unjustified absence at the TP will lead to a zero as TP grade. Skills will be evaluated through the lab session reports and the written exam. Skills C1.2 and C1.3 will be deepened during the lab sessions.

Course support, bibliography

- Dynamical Systems in Neuroscience: The Geometry of Excitability and Bursting, Eugene M. Izhikevich, The MIT Press, 2007
- Nonlinear dynamics and Chaos, by Steven Strogatz, Westview Press, 2001
- Mathematical Foundations of Neuroscience, by G. Bard Ermentrout & D. Terman, Springer, 2010
- Theoretical neuroscience, by P. Dayan & L.F. Abbott, The MIT Press, 2005

Resources
A multi-disciplinary teaching team, including researchers in computational neuroscience, a neurosurgeon, a professor in control theory and a start-up creator.

Practical works will be made on computers with Matlab-Simulink.

Learning outcomes covered on the course

At the end of this course, students will have acquired basic neuroscience knowledge to allow interaction with professionals of the field (neurosurgeons, computational neuroscientists, experimenters). They will know of mathematical tools to model activity of a single neuron or a whole neuronal population, and to predict their dynamical properties both analytically and through simulations. They will also have been made aware of opportunities offered by neuroscience in terms of research, medical and industrial development, and entrepreneurship.

Description of the skills acquired at the end of the course

By the end of this course, students will be able to:

- Understand neuroscience fundamentals, for possible interaction with professionals of the field (neurosurgeons, computational neuroscientists, experimenters)
- Model the activity of a neuron or a whole neuronal population
- Predict their behavior both analytically and numerically.

This course will thus be an opportunity to deepen skills:

- C1.2: "Use and develop adequate models, choose the right modeling scale and the right simplifying assumptions to treat a problem": Jalon 3
- C1.3: "Solve a problem by employing approximation, simulation and experiments": Jalon 2A
- C1.5: "Use a wide scientific and technical background in the context of a transdisciplinary approach"
- C2.2: "Transpose to other fields, generalize knowledge"
- C2.3: "Quickly identify and acquire new knowledge and skills in relevant domains (technical, economical or other)".