2EL2630 – Applications of statistical and quantum physics to information science

Instructors: Zeno Toffano
Department: DÉPARTEMENT SIGNAL, INFORMATION, COMMUNICATION
Language of instruction: ANGLAIS
Campus: CAMPUS DE PARIS - SACLAY
Workload (HEE): 60
On-site hours (HPE): 35,00
Elective Category : Fundamental Sciences
Advanced level : Yes

Description

This course is an opening to mathematical, informational and statistical theories and methods issued from statistical and quantum physics used in information science.

These methods are currently applied in many fields related to information processing, neural networks and deep learning, image processing, telecommunications, the semantic web, artificial intelligence, computational biology... but also more generally in the humanities and social sciences with, for example, applications in natural language processing and in finance.

The notions of entropy and information are central to this approach. For example, the study of disordered spin systems is applied to the processing of discrete information and statistical inference with important applications for example in telecommunications. More recently, operational techniques using quantum information have shown their advantage over conventional methods, the emblematic example being the quantum computer.

The purpose of the course, which is transdisciplinary in nature, is to establish connections between the training in mathematics and physics and advanced technological applications, such as digital communications, data processing, algorithmic learning and also quantum computation and information. It is intended for students wishing to familiarize themselves with research and engineering topics in top scientific and technological fields in a digital environment.

Quarter number

SG8

Prerequisites (in terms of CS courses)
analysis and probability theory, linear algebra, quantum and statistical physics and modeling.
Desired notions in information theory, machine learning, communications theory, algorithmic and complexity theory.

Syllabus

Overview and general concepts
- Scientific, historical and application panorama around the evolution of the concept of entropy in physics and information theory.
- Recent developments: from physics to information and communication sciences, to artificial intelligence and also social and life sciences.

Statistical physics, inference, and computing
- Thermodynamic equilibrium as a calculation instrument: Gibbs fields and potentials, Boltzmann machines.
- Local interaction models (Ising and generalizations) and Bayesian inference. Application to the estimation of noisy images.
- Markov dynamic models and graphs: belief propagation algorithm, factor graphs, performance of neural network models, analysis of phase transitions in complex systems.

Statistical physics and information and communication theory
- Information measures: Shannon entropy, relative entropy, differential, mutual information, inequalities, other forms of entropy (Fisher, Renyi, Tsallis ...)
- Information and communication theory: source entropy, data compression, capacity and coding theorems of a communication channel.

Quantum information
- Consequences of the quantum mechanics postulates: the quantum measurement problem, quantum superposition and composition, von Neumann entropy, no-cloning and entanglement.
- Quantum computing: quantum qubits and circuits, parallel and probabilistic calculations, quantum algorithms for inference and optimization, quantum random walks and quantum simulation of physical systems.
- Applications: quantum communications and cryptography, quantum error correction, quantum tomography and estimation, quantum control, quantum optimization and machine learning.

Class components (lecture, labs, etc.)
33 HPE main and appliication courses

Grading
2 hour examination
personal work: oral presentation with slides of a scientific paper

Course support, bibliography
Nishimori H., “Statistical Physics of Spin Glasses”, Clarendon 2001.
Opper M., Saad D. (Eds.) Advanced Mean Field Methods, MIT 2001
Mézard M., Montanari A., “Information, Physics, and Computation”, Cambridge, 2009.
Nielsen M., Chuang I., “Quantum Computation and Quantum Information”, Cambridge, 2001
Jaeger G., “Quantum Information: An Overview”, Ed. Springer 2007.

Resources
• Teaching team (names of lecturers) :
A.O. Berthet , M. Pourmir , Z. Toffano

Learning outcomes covered on the course
At the end of this course the student will be able to:
1) Understand in a multidisciplinary context the importance and impact of classical or quantum concepts of information and entropy
2) Using the mathematical tools of Statistical and Quantum Physics, interpret concrete cases, for example in the field of data sciences, telecommunications, artificial intelligence, computational biology or finance.
3) Propose mathematical models for innovative applications such as machine learning, neural networks, optimization, information networks, quantum computers, etc. using the means of information theory, statistical inference, optimization criteria, logic and quantum information learned during the course.
4) Implement mathematical models in the form of algorithms in different computer environments.

Description of the skills acquired at the end of the course
Learning outcomes 1 and 2 allow to reach the milestone 1 of the C1.1 skill, *ie* "Know how to make the influence of peremeters influent on the analysed system, the list of the elements with which it is in relation "and" Knowing how to identify important parameters with respect to the given problem".
Learning outcomes 3 and 4 enable to reach milestone 1 of skill C 1.2, that is, "Knowing how to use a model presented in the classroom in a relevant

way." Making the choice of the simplifying hypotheses adapted to the problem".
Learning Outcome 4 also achieves milestone 2B of skill C 1.3, ie "Knowing the limitations of numerical simulations and what can be expected, namely, to criticize numerical simulation results. ".