Complexity, Criticality and Consciousness.

Ten lectures on the **physics of complex systems applied to biological sciences**

Intensive course by prof. Dante R. Chialvo, CONICET, Buenos Aires (Argentina)

Lectures are planned on Tuesdays, room D-2-02 at 3 p.m.

Brief description of the course

Results over the last decade in the area of statistical physics show nontrivial similarities between the behaviors of complex systems of various origins, whether biological, social, behavioral, political, environmental or technological.

One such aspect is the spontaneous emergence of **complex** structures from the interactions of the individual components of the system. Studies have revealed that such emergence occurs more often near instabilities, in the boundaries between stable regimes, i.e. near **criticality**. The comparative analysis of such **complexity and criticality** across systems and disciplines already advanced our understanding of a variety of complex systems.

The success of these novel approaches increased the interest in the use of similar tools for the analysis of the brain, aimed to understand the spatio-temporal organization of large-scale brain in health and disease. Similar interest percolated to other areas of biology.

These ten lectures encompass a chronological account of research results covering the last decade. The course starts with a discussion of what is complexity in nature, as the object of interest. About middle way the overambitious hypothesis that **complexity is always critical** is presented and supported with a variety of examples and counterexamples. The last third is dedicated to the study of brain dynamics, advancing the hypothesis that the **brain is complex because is critical**. Our state of awareness (consciousness) is also discussed presenting results that suggest **we are conscious whenever our brain is critical.** Finally other "brains" are discussed including the collective organization of proteins, macromolecules and gut microorganisms. The closing of the lectures are dedicated to discuss practical projects on how to extend similar ideas to the students' system of interest.

Schedule

Lectures are planned on Tuesdays, room D-2-02 at 3 p.m.

The material presented is suitable for graduate students of Engineering, Physics, Medical sciences and Biology.

Evaluation: Monograph/Project.

More information: Contact Dante Chialvo, dchialvo@gmail.com

Detailed content of the lectures:

-*Initial motivational lecture* (Unit 0)

Unit 0: How complexity emerges: why these ideas are too important to leave it only to the *cognoscenti.*

-*Complexity* (Units 1 & 2)

Unit 1: Introduction to the sciences of complexity with emphasis on applications in biological, physical sciences and engineering.

Unit 2: Complex networks as the "skeleton" of a complex system. How a network is defined by the flow of interactions between places. Simple examples from social, biological, linguistic, transportations and engineering systems. Concepts of Robustness and Fragility in networks. Static networks and evolving networks. Basics aspects (structural and topological) of networks. The "network zoo": ordered, disordered, small world, scale free, hierarchical, visibility, etc networks.

-*Criticality* (Units 3, 4, 5)

Unit 3: What is a phase transition and what it means for a system to be critical. General notions of critical phenomena. How complexity, in nature, emerges from simplicity. Self-organized criticality.

Unit 4: Criticality in the brain. Why the brain shall be critical. Initial experiments in collection of neurons. Neuronal avalanches in brain slices. Models. Further questions

Unit 5: Criticality in the brain at large scale. Neuroimaging. Introduction to the physics of magnetic resonance: structural and functional imaging. Introduction to the physiology of magnetic resonance: what measures functional MRI? Study of functional and structural connectivity of the human brain. Linear correlation maps based on seeds, triggered averages, point processes and edges. Correlation length and Correlation time. Dynamic scaling. Characterization of large scale dynamics, order and control parameters.

-*Heuristic metrics of brain states: Consciousness* (Units 6 &7)

Unit 6: Large-scale mathematical models of the brain. Numerical study of phase transitions in neural mass models. Comparison with experimental results obtained with MRI.

Unit 7: Altered mind states: Loss of consciousness. How to objectively measure any given mind state? Discussion of recent results and probable future work in this area.

-*Beyond brains (Units 8 & 9)*

Unit 8: Organelles and Macromolecules: Critical dynamics of signaling proteins and mitochondria.
Unit 9: The complex dynamics of the gut microbiome.

-*Class Projects*

Discussion of specific projects related to the course topics

Bibliography

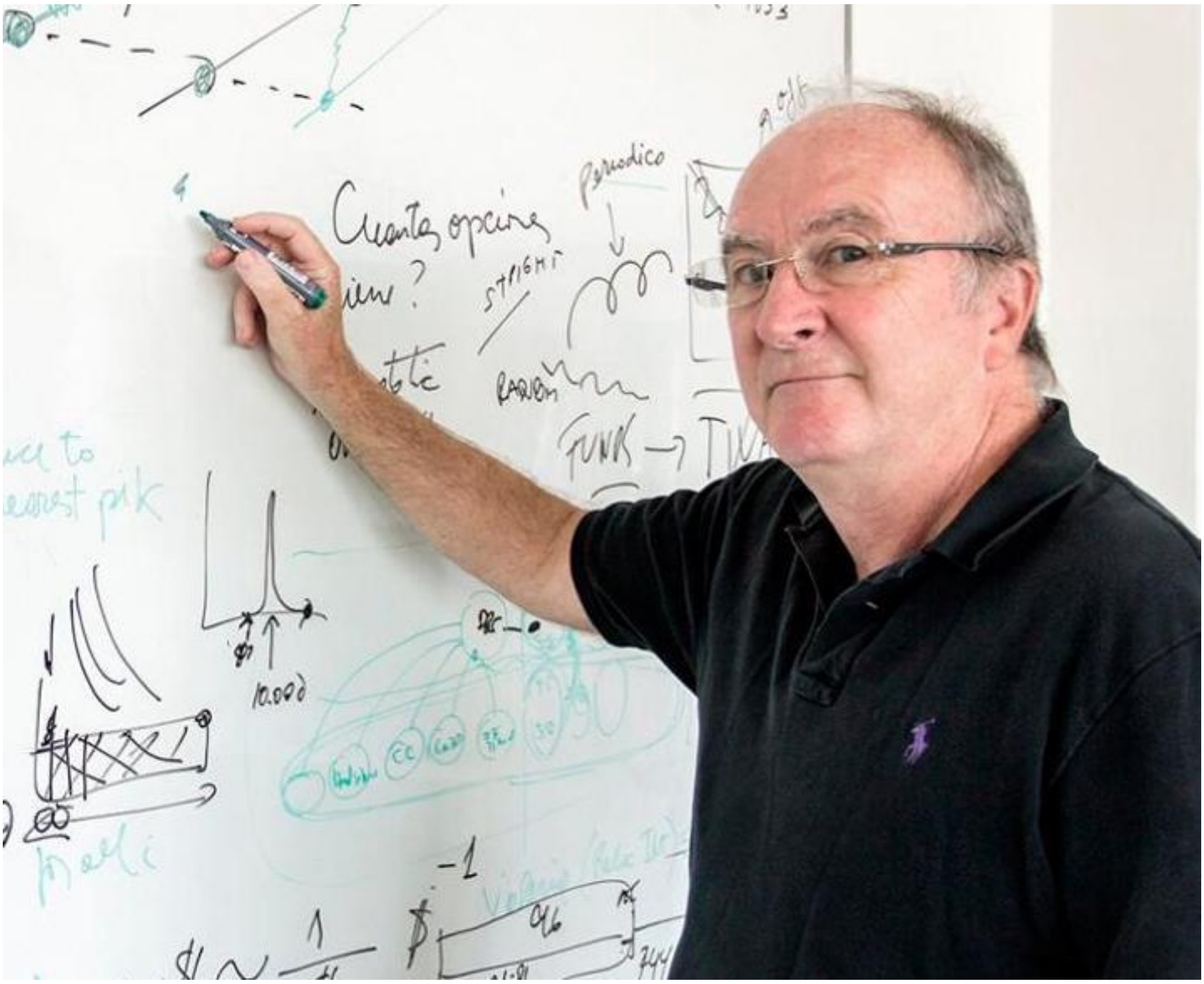
General Reading:

- Per Bak. How nature works: the science of self-organized criticality. Copernicus, 1999.

To be discussed in class:

- D R Chialvo. Emergent complex neural dynamics. Nature Physics, 2010.
- D R Chialvo, SA Cannas, TS Grigera, DA Martin, D Plenz. Controlling a complex system near its critical point via temporal correlations. Scientific reports 10 (1), 1-7
- E. Tagliazucchi and DR Chialvo. Brain complexity born out of criticality. AIP Conference Proceedings, 1510(1):4–13, 2013.
- Chialvo DR, Gonzalez Torrado AM Gudowska-Nowak E, Ochab JK, Montoya P, Nowak MA, Tagliazucchi E. How we move is universal: scaling in the average shape of human activity. Paper in Physics, 7(2) 2015.

- E Tagliazucchi, DR Chialvo, M Siniatchkin, E Amico, JF Brichant, … Large-scale signatures of unconsciousness are consistent with a departure from critical dynamics. Journal of The Royal Society Interface 13 (114), 20151027 (2015)
- Tagliazucchi E, Carhart-Harris R, Leech R, Nutt D, Chialvo DR. Enhanced repertoire of brain dynamical states during the psychedelic experience. Human Brain Mapping, (2014).
- Haimovici A, Tagliazucchi E, Balenzuela P & Chialvo DR. Brain organization into resting state networks emerges from the connectome at criticality. Physical Review Letters (2013).
- Fraiman D. & Chialvo DR. What kind of noise is brain noise: Anomalous scaling behavior of the resting brain activity fluctuations. Frontiers in Fractal Physiology. (2012)
- Tagliazucchi E, Balenzuela P, Fraiman D & Chialvo DR. Criticality in large-scale brain fMRI dynamics unveiled by a novel point process analysis. Frontiers in Fractal Physiology. (2012)
- Dante R. Chialvo. Emergent complexity: What uphill analysis or downhill invention cannot do. New Ideas in Psychology, 26(2):158 – 173, 2008.
- Expert P, Lambiotte R, Chialvo DR, Christensen K, Jensen HJ, Sharp DJ & Turkheimer F. Self-similar correlation function in brain resting-state functional magnetic resonance imaging. Journal of The Royal Society Interface 8, 472-479 (2011).
- Chialvo DR. Are our senses critical? Nature Physics 2, 301 (2006).
- Eguiluz V, Chialvo DR, Cecchi G, Baliki M, Apkarian AV. Scale-free brain functional networks. Phys. Rev. Letters 92, 018102 (2005).
- Pellegrini GL, de Arcangelis L., Herrmann HJ, Perrone-Capano C Activity-dependent neural network model on scale-free networks, Phys. Rev. E, 76, 2007
- Chialvo DR and Bak P. (1999) Learning from mistakes. Neuroscience 90 (4) 1137–1142
- N Zamponi, E Zamponi, SA Cannas, OV Billoni, PR Helguera, DR Chialvo Mitochondrial network complexity emerges from fission/fusion dynamics. Scientific reports 8 (1), 1-10
- Y Tang, YY Zhang, J Wang, W Wang, DR Chialvo. Critical fluctuations in the native state of proteins Q Phys. Rev. Letters,118 (8), 088102
- DR Chialvo. Life at the edge: complexity and criticality in biological function Acta Physica Polonica B, vol. 49, issue 12, p. 1955 (2018)



Supplementary reading:

• Maki-Marttunen V, Diez I, Cortes JM, Chialvo DR, Villarreal M. Disruption of transfer entropy and inter-hemispheric brain functional connectivity in patients with disorder of consciousness., Frontiers in Neuroinformatics (2013).

• Lombardi F, Chialvo DR, Herrmann HJ, de Arcangelis L. Strobing brain thunders: functional correlation of extreme activity events. Chaos, Solitons & Fractals (2013).

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• Tagliazucchi E, Laufs H, Chialvo DR. A few points suffice: Efficient large-scale computation of brain voxel-wise functional connectomes from a sparse spatio-temporal point-process. arXiv preprint arxiv.org/abs/1409.6378