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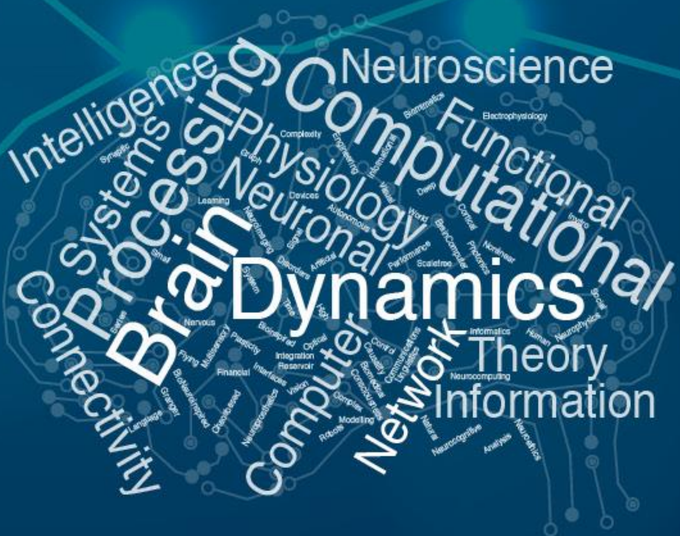
Lecture abstracts



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Angelo Bifone

University of Turin & Italian Institute of Technology, Italy

Review: Brain functional connectivity and neuropsychiatric disorders: lost in translation

Abnormal brain resting-state functional connectivity, as measured by functional MRI and other neuroimaging techniques, has been consistently observed in patients affected by neuropsychiatric disorders. Graph theoretical methods provide a framework to investigate these defective functional interactions and their effects on the organization of brain connectivity networks. In this lecture, I will review some of these methods and discuss their contribution to the study of the topological structure of functional connectivity in the healthy and diseased brain.

Despite recent progress, however, the question whether aberrant functional connectivity plays a role in the etiology of these complex brain conditions remains open. To this end, I will discuss translational strategies, including investigations in patients and disease models, that may help elucidate the relation between functional connectivity, and brain function or dysfunction.

Roger Dangel

IBM Research Zurich, Switzerland

Tutorial: Analog Crossbar Arrays - Future Neuromorphic Workhorses for Neural Networks

For the learning ("training") and use ("inference") of Artificial Neural Networks, digital (co-) processors (CPUs, GPUs, FPGAs and ASICs) in computer systems based on Von-Neumann architecture are used almost exclusively today. One promising alternative to these costly and energy-hungry digital logic based computer systems is Analog Neuromorphic Computing, where computationally time-consuming and therefore expensive operations are performed by specialized accelerators comprising analog elements with the promise to accelerate existing schemes by factors of 1000 to 10,000.

In general, suitable compute elements are programmable analog resistive or optical devices with non-volatile memory capabilities that can be arranged in crossbar arrays to perform various mathematical operations. The main requirements for such emerging "non Von-Neumann" architectures are vector-matrix multiplications and the ability to provide the transposed matrix for learning as well as means to store analog synaptic weights. This mitigates the huge communication overhead for the operands in traditional systems, i.e. avoids the time and energy consuming massive data shuffling between processor and memory.

Review: Photonic Processing Unit - Acceleration of Neural Network Training Based on Analog Optical Crossbar Arrays

In the Neuromorphic Devices and Systems group at IBM Research – Zurich, we are working on an optical integrated analog compute engine (Photonic Processing Unit) for learning and inference of Deep Neural Networks. This compute engine exploits 2-dimensional holographic interference patterns which lead to refractive index gratings in photorefractive, semi-insulating thin III/V films integrated with silicon photonics circuits. This approach facilitates and accelerates matrix-vector multiplications, as required for the Backpropagation Algorithm of Deep Neural Networks, performed in an analog way, analogous to analog electrical crossbar arrays. These analog "optical crossbar arrays" feature very high linearity, high dynamic range and synaptic matrix weights that are optically stored within the photorefractive thin III/V layer. This entire optical accelerator technology should be packaged and thus provide standard electrical interfaces to integrate and interface seamlessly with other AI system components.

Lucilla de Arcangelis

Department of Engineering and INFN, University of Campania "Luigi Vanvitelli", Italy

Tutorial: Physics of complex systems and criticality

Phase transitions, like the boiling of water upon increasing temperature, are a part of everyday experience and are yet, upon closer inspection, unusual phenomena, revealing fascinating features. Comprehending key aspects of phase transitions has lead to the uncovering of new ways of describing matter composed of large numbers of interacting elements, which form a dominant way of analysis in contemporary statistical mechanics. An introductory discussion is presented here of the concepts of criticality, scaling, universality and scale invariance. In nature, a variety of systems exhibit the emergence of a macroscopic behavior, unpredictable on the basis of microscopic laws. The absence of a characteristic size and power law behavior is detected even in the absence of a control parameter as the temperature. Different complex natural systems are presented, stressing the origin of complexity and introducing the concept of self-organized criticality. Moreover, the crucial role of long-range spatio-temporal correlations is enlightened, discussing some of the fundamental tools able to evidence their existence.

Review: Criticality as a signature of healthy neural systems

Recent experiments have shown that the spontaneous brain activity is characterized by the presence of avalanches showing absence of characteristic size. These results can be successfully interpreted in the context of self-organized criticality. In this lesson a neural network approach inspired by self-organized criticality is introduced and discussed for network morphologies. In particular, the origin of the "universally" measured exponents for size and duration distributions is addressed, as well as the role of modular networks, statistically similar to the structure of the human brain, on the non-epileptic avalanche activity. The presence of long-range correlations can be evidenced by the power spectrum of the neuronal signal, measured by electroencephalogram (EEG), exhibiting an important dependence on the percentage of inhibitory neurons. The presence of these correlations can be highlighted in greater detail through the distribution of inter-times between neuronal avalanches. We will present experimental and numerical results that confirm the existence of temporal correlations. Moreover, this statistical analysis allows to highlight the complex temporal organization of avalanches of different sizes, which results in the oscillations in high and low frequency usually observed in the EEG spectrum. For all these properties we will discuss the different behavior exhibited by healthy, "critical" systems versus epileptic, "supercritical" ones.

Athena Demertzi

University of Liège, Belgium

Tutorial: Resting state fMRI as a means to assess the consciousness after severe brain injury

Consciousness is a complex construct with no universal definition. Especially in pathological conditions how can one reliably observe and measure it? Behavioural evaluation is not straightforward, despite systematic assessments, due to patients' physical and cognitive condition. Yet, the diagnosis of disorders of consciousness has been notably facilitated by means of technological modalities. Here, we will see how systems-level functional neuroimaging has assisted clinical evaluation, how it can potentially be informative of clinical outcome, and what these findings teach us about typical conscious states. As this type of research touches upon philosophical and ethical issues, we will discuss the emerging neuroethical concerns stemming from the research of this challenging population.

Review: Quantifying conscious level by means of intrinsic brain connectivity

Consciousness is seemingly lost and recovered every day, from the moment we fall asleep until we wake up. Although these departures from wakefulness bring about different changes in brain function, behavior, and neurochemistry, they all lead to lack of reported subjective experience. Here, I will show how the temporal dynamics of ongoing brain activity have characterized different states of unconsciousness, such as sleep, pharmacologically-induced anesthesia in humans and animals, and in noncommunicating states following to brain injury. By and large, these investigations indicate that during unconscious states cortical long-range correlations are disrupted in both space and time, anticorrelated cortical interactions disappear, and the dynamic explorations are limited to specific patterns which are dominated by rigid functional configurations tied to the anatomical connectivity.

Mukesh Dhamala

Department of Physics and Astronomy, Neuroscience Institute, Atlanta, Georgia State University, USA

Tutorial: Granger causality: theory and appications to neuroscience data

Granger causality is a statiscially principled technique to extract diretions of information flow from multivariate time series data. There are time- and frequency-domain measures of Granger causality, which can be estimated either by autoregressive data modeling or by factorization of spectral matrix of the data. Research over the years have shown that careful applications of Granger causality to multielectrode neurophysiological recordings and high-resolution neuroimaging data can provide new insights into hierarchical functional organization of the brain. In this lecture, I will describe the main idea of Granger causality, the mathematics of estimation approaches with simulation examples, address recent controversies, and present some application examples to real data, including LFPs, intracortical EEG, scalp EEG and rfMRI.

Review: Oscillatory Network Activity in Brain Functions and Dysfunctions

Synchronized neuronal oscillations and oscillatory interactions within distributed brain regions are known to be central to normal perceptual and cognitive functions. Breakdowns or changes in interaction and synchronization within the network of brain regions can be indicative of brain dysfunctions. Understanding network oscillations and interactions can thus not only provide insight into the physiological mechanisms for sub-processes in higher-level cognition but also assist in the diagnosis and treatment of brain disorders. In this lecture, I will present a review of our recent findings of oscillatory network activities underlying perceptual decision-making processes, stroke recovery, and epileptic seizures.

Wlodzislaw Duch

Neurocognitive Laboratory, Center for Modern Interdisciplinary Technologies, Nicolaus Copernicus University, Poland

Tutorial: Multi-level explanations in neuroscience I: From genes to subjective experiences

Understanding brain dynamics, control of behavior and mental processes is the ultimate challenge for science. It requires multi-level explanations, starting from evolutionary pressures, genes, proteins, cells, networks of neurons, psychophysics, subjective experiences at the mental level, and social interactions. Many branches of science contribute to development of neurocognitive phenomics. Physics provides experimental and theoretical tools at the molecular and brain signal processing level, and mathematical tools at the level of neurodynamics. Inspirations from understanding brains are of great practical importance in many fields, including neuropsychiatry, neuropsychology and artificial intelligence. Neurodynamics provides the best language to link low-level molecular phenomena to high-level cognitive functions. Computational simulations help to understand molecular dynamics and analyze real brain signals. This is a very fruitful area of research that requires global, interdisciplinary effort of experts from many branches of science.

Review: Searching for fingerprints of brain cognitive activity and their applications.

Great progress has been made in recent years in methods of measurement and analysis of neuroimaging and electrophysiological data, reading and interpreting brain signals. Extracting "fingerprints" of active brain regions or subnetworks from EEG data will open the path to many applications: reliable brain-computer interfaces, diagnostic methods in neuropsychiatry, therapeutic interventions using neuromodulation, optimization of brain processes through neurofeedback or behavioral procedures, and interpretation of some mental states.

I shall review several approaches that help to identify specific brain activity from high density EEG signals, based on spectral fingerprints, source reconstruction and localization, and functional network science analysis. Recent methods of data preprocessing, realistic models of ionic currents conduction through various brain tissues, methods of reconstruction of potentials measured by the EEG sensors and connectivity analysis allows to achieve results that in some cases can be compared with those obtained from functional MRI.

Duch, W. Mind as a shadow of neurodynamics. Physics of Life Reviews, Special Issue "Physics of mind" (in print).

Luca Faes

Department of Engineering, University of Palermo, Italy

While functional segregation and integration are known mechanisms studied in large-scale brain networks, the same principles can be applied to the entire nervous system and encompass interactions between brain and body. In the emerging paradigm of Network Physiology, the human organism is viewed as an integrated network where the brain and the peripheral systems (cardiovascular, respiratory, muscular, and others), each with its own internal dynamics, continuously interact with each other to support physiological function and establish system-wide integration across different states. In this context, devising proper analysis frameworks and providing empirical measures to assess information processing in brain networks formed by coupled neuronal units, or in physiological networks formed by different organ systems, may yield fundamental insight on the dynamics of these networks and on the related neurophysiological processes.
In the two lectures, I will introduce an unifying approach for the quantitative description of brain and physiological networks framed in the novel research field of information dynamics. The approach is based on interpreting the network nodes as dynamical systems, mapping the system behavior into a set of variables, and describing the time evolution of these variables –collected in the form of time series– using information-theoretic tools.

Tutorial: Information-Theoretic Analysis of Brain and Physiological Networks: Methods

In the first lecture, the framework of information dynamics will be first formalized theoretically dissecting the general concept of 'information processing' into essential sub-components of meaningful interpretation: the new information produced by a dynamical system at each moment in time, the information stored in the system, the information transferred to it from the other connected systems, and the informational character (synergistic or redundant) of the information transferred from multiple source systems to a target system. The associated measures of information storage, transfer and modification, will be presented together with the methods for their empirical computation from time series data.

Review: Information-Theoretic Analysis of Brain and Physiological Networks: Applications

In the second lecture, the practical computation of these measures to the analysis of brain and physiological networks will be presented. Applications will include the analysis of resting state brain networks probed through EEG and fMRI signals, the study of the transitions from wake to sleep and across different sleep states in healthy subjects and sleep apnea patients, the analysis of how mental stress alters brain-body interactions, the identification of functional connections within the distributed motor system during postural control, and the detection of spatially distributed brain-heart information transfer during visual emotion elicitation.

Alessandro Gozzi

Italian Institute of Technology, Italy

Tutorial: Networks of spontaneous brain activity in the rodent brain

Spontaneous neural activity as measured with resting state fMRI (rsfMRI) is widely used to infer the brain’s intrinsic functional organization and connectivity. rsfMRI mapping in humans have consistently revealed reproducible “functional connectivity” networks underlying known (e.g. motor, auditory, visual, salience) as well as less understood (e.g. default mode network - DMN) cognitive functions. Importantly, evidence of aberrant rsfMRI connectivity has been accumulating for several brain disorders, such as schizophrenia and autism. However, the neural basis and etiopathological significance of these aberrancies remain largely unknown.
The study of macroscale functional connectivity in rodents, where genetic and environmental conditions can be controlled and manipulated with high specificity, offers the opportunity to elucidate the biological determinants of these alterations. In my talk I will summarize some key results of this recent line of inquiry, highlighting remarkable correspondences between rodent and human intrinsic neural network organization. Emphasis will be given to the use of this paradigm to probe brain dysconnectivity in mouse lines harboring mutations associated to autism. Through this approach, causal relationship between connectivity alterations, genetic etiologies and neuro-developmental aberrations can be established, with the final goal of generating translationally-relevant hypotheses about the origin of these perturbations, and make biological sense of the highly heterogeneous connectivity findings in the autism spectrum.

Review: Oscillatory dynamics in networks of brain activity during rest

Spontaneous brain activity as assessed with resting-state fMRI exhibits rich spatiotemporal structure. In my talk I will illustrate the use of frame-wise clustering approaches to map spatiotemporal dynamics of spontaneous fMRI activity with voxel resolution in the resting brain. These methods allows the reliable identification of brain-wide patterns of fMRI co-activation at the group and subject level, defining a set of recurring states characterized by rich network structure. Through this approach, fMRI states characterized by coupled oscillatory network dynamics have been identified, with each network state occurring at specific phases of global fMRI signal fluctuations. Preliminary evidence linking autism-associated genetic alterations to atypical functional states and altered infraslow dynamics will be presented. These recent results point at oscillatory network dynamics as a novel, fundamental principle guiding the spatiotemporal reconfiguration of resting state fMRI activity, and its breakdown in brain disorders.

Sergio Martinoia

University of Genova, Italy

Tutorial: Micro-Electrode Arrays technology and in vitro neuronal models

Neurons from animal embryos (or newborns) extracted from specific areas of the Central Nervous System (CNS) can be cultured in vitro under appropriate conditions, and chronically coupled to electronic devices (Micro-Electrode-Arrays, MEA). After a few days, neurons connect each other with functionally active synapses, forming a complex network and displaying spontaneous electrophysiological activity. First, I will introduce the basic concept of MEA technology and present the most common and used devices for network electrophysiology. I will then present protocols and procedures to implement 2D networks coupled to MEA devices, 2D patterned-interacting-interconnected networks and 3D network models. Basic concept of extracellular recordings and network electrophysiology will be introduced.

Review: Advanced neuro-electronic interfaces coupled to engineered neuronal assemblies: network dynamics and connectivity

2D and 3D engineered neuronal networks coupled to advanced neuro-electronic devices can be used for studying the dynamic behavior and interaction among neuronal populations. They also constitute a well-established experimental in vitro platform to study fundamental mechanisms of brain (dys)function but they are also becoming widely used for neuropharmacological screening and neurotoxicity tests. I will introduce these experimental models coupled to new electronic interfaces (CMOS based devices, organic-based transducers). Finally, I will address the fundamental question of multisite neural signal deciphering-analysis by proposing a framework of study in which functional and structural connections are investigated with revisited methods based on cross-correlation and information theory.

Ludovico Minati

Tokyo Institute of Technology, Japan; Polish Academy of Science, Kraków, Poland; University of Trento, Italy

Review 1: Connectivity and synchronization: comparison of neural observations and experiments with toy networks

Review 2: Remote synchronization: detailed account of a peculiar pattern-formation mechanism

Review 3: More non-linear circuits: integrated implementation, versatile motor pattern generation, criticality

The non-linear dynamics of neurons represent the ultimate substrate through which the diversity of mental states and processes making up our subjective experience emerges from the brain as a physical object. While contemporary engineering preferentially focuses on linear dynamical systems and devices owing to their usefulness and vastly easier mathematical tractability, non-linear phenomena pervade nature at all scales and harbor immense generative potential. Such phenomena have aspects of universality and therefore can be elicited, among other possible scenarios, also in analog electronic networks containing one or more non-linear elements, which are particularly convenient to realize and study experimentally. Here, a condensed review of the author's own work in this area is presented. First, atypical circuits based on bipolar-junction transistors, inverter gates and glow lamps are introduced, which replicate, at least phenomenologically, certain aspects of neural dynamics such as the generation of irregular spike trains. Second, the spontaneous emergence of synchronization patterns featuring modular organization and remote entrainment or implementing viable walking gaits is demonstrated in networks constructed of those circuits. Some reflections on the potential contribution of comparing such profoundly different physical systems and possible directions for future work are finally given.

Claudio Mirasso

University of the Balearic Islands, Spain

Review: Synchronization of neuronal circuits: modeling and dynamics

Synchronization has been extensively studied in the brain, where it has been hypothesized to be relevant to issues such as the binding problem, temporal coding, deployment of spatial attention, higher cognitive functions, and many others.

In this class we will develop the basic concepts that lead to the modelling of the dynamics of neurons and their interactions. Starting from concepts such as membrane potential, ionic currents, and synapses, we will build mesoscopic models that describe the emerging properties of neuronal circuits.

As an example, we will analyze two types of synchronization that can play an important role in the brain: zero-lag synchronization and anticipated synchronization.

Thomas Nowotny

University of Sussex, UK

Tutorial: Multi-scale modelling of neural circuits

In this lecture I will give an introduction into multiple types of models for brain circuits. Starting with the classic Hodgkin-Huxley model for electrically active neuronal membranes, I will discuss the origin of the equations, how to interpret them confidently and how to simulate them. I will explain how to assemble networks of spiking neurons and how to simulate synapses. Then I will give a brief summary of other levels of modelling, including integrate-and-fire and rate models. The tutorial will end with some advanced considerations of how to systematically reduce spiking neural networks into quantitatively matching rate models. Time permitting, I will also briefly discuss simulation tools, including our own GPU enhanced Neuronal Networks (GeNN) tool (https://github.com/genn-team/genn).

Review: Insect solutions to olfaction and visual navigation

In this review lecture I will discuss the fundamentals of insect olfaction and present a model of odour arrival discrimination in bees (Nowotny et al., 2013). In brief, bees are able to discriminate whether two odorants arrive synchronously or with a slight delay, down to delays of only 6 ms (Szyszka et al., 2012). How this can be achieved with neuronal “wetware” where individual spikes are already 1-2 ms wide, is challenging. I will present and discuss our HH-based computational model that implements rapid winner-take-all attractor dynamics to disambiguate between odorant arrival conditions. In a second story on insect olfaction, I will discuss our recent results that mixtures must be perceptually more stable across concentrations given quite parsimonious assumptions on how odor receptors work (Chan et al., 2018).

In the remaining time of the lecture I will give a few highlights of the principles of visual navigation in ants and bees, which underlie our current Brains-on-Board project (http://brainsonboard.co.uk/). After introducing the motivation, fundamental concepts and hypotheses I will show some spotlights of our current research and future plans in the project.

T. Nowotny, Jacob S. Stierle, C. Giovanni Galizia, Paul Szyszka (2013) Data-driven honeybee antennal lobe model suggests how stimulus-onset asynchrony can aid odour segregation, Brain Research, 1536: 119-134. 10.1016/j.brainres.2013.05.038

P. Szyszka, J.S. Stierle, S. Biergans, C.G. Galizia (2012) The Speed of Smell: Odor-Object Segregation within Milliseconds. PLOS ONE 7(4): e36096. https://doi.org/10.1371/journal.pone.0036096

H. K. Chan, F. Hersperger, E. Marachlian, B. H. Smith, F. Locatelli, P. Szyszka, T. Nowotny (2018) Odorant mixtures elicit less variable and faster responses than pure odorants. PLoS Comp Biol 14(12):e1006536. doi: 10.1371/journal.pcbi.1006536

Lorenzo Pavesi

University of Trento, Italy

Review: Neuromorphic photonics

Recently, Artificial Neural Networks (ANNs) have become gradually more accessible and tackle problems of increasing complexity, leading to dramatic improvements in Artificial Intelligence. The drive to increase the efficiency of the ANN computation operations is very strong. Usually, ANNs are run on standard (von Neumann-based) computers, in which the CPU is accelerated by ASICs (GPUs). However, new computational architectures can potentially largely speed-up the ANN processing time. This motivates our investigation; we focus on the advantages of silicon photonics in order to build a new architecture which can efficiently execute ANN tasks. Specifically, using integrated photonics structures, we aim to develop a Feed-Forward Neural Network architecture where we physically implement one of the most critical ANN components: the "activation function".

The physical device which performs the activation function is a single microring resonator in the Add-Drop Filter configuration (ADF). In this configuration, the microring is coupled with two waveguides in order to inject and extract the light signal. We characterized its (thermal) nonlinear response, which will be used as the activation function. In addition, we show that the interplay between different nonlinearities causes oscillatory behaviour in the mircoring response which can be used to implement recurrent ANN. We do discuss the performances of these networks.

Finally we do conclude by introducing the concept behind the BACKUP project where living neurons and photonics circuits merge into an hybrid ANN (https://r1.unitn.it/back-up/).

Concetto Spampinato

University of Catania, Italy

Tutorial: Neural Data Analysis in the Deep Learning Era

This talk first introduces the basic concepts of deep learning methods presenting convolutional neural networks, recurrent neural networks and generative adversarial networks and their design principles. Then the talk focuses on an overview of the most recent DL methods applied to EEG data analysis discussing about data, preprocessing methodology, DL design choices, and results. The tutorial concludes with some recommendations on how to design and publish future studies in the field.

Review: Reverse-brain engineering: Decoding Brain Visual Representations using AI

This talk presents some a few recent efforts combining Artificial Intelligence and Cognitive Neuroscience fields for improving our understanding on how the human brain processes the visual world.
It will then present a strategy for decoding spatio-temporal brain processes related to the human visual system and for interpreting deep learning models using biologically-inspired concepts.

Natsue Yoshimura

Tokyo Institute of Technology, Japan

Review 1: Brain-computer interface (Invasive, Non-invasive, EEG)

This talk will introduce basics and trends of brain-computer/machine interfaces (BCI/BMI) and future possibility of non-invasive brain activity recording methods.

Review 2: Neural decoding using non-invasive brain activity signals. (Machine learning, motor control, fMRI)

Focusing on decoding information about motor control, this talk will introduce a few studies from the speaker's works that used EEG and fMRI.