Special Session 18: Concepts, architecture and dynamics of non-standard computations

Ruedi Stoop, Swiss Federal Institute of Technology Zurich, Switzerland

This session is devoted to the mathematical analysis of non-standard computations. What are their architectures, how do these architectures influence their performance, and how can this performance be measured?

Any real computation is at its root a physical dynamical process that must play out in a physical medium. Whereas the classical machine model of computing consists of digitally specified states, and specified operators that transform states one to another, nature offers many different dynamical processes that, although they could be identified as computations, rely on rather different principles. For neuronal systems, e.g., it is difficult to grasp what the underlying natural codes are, and how they are realized in the neuronal architecture. Understanding such alternative computational paradigms is of great importance because - as in the mentioned example - they may have efficiency and stability features that reach far beyond those provided by classical computation.

Mathematically well-founded general and exemplary contributions that center around these topics are welcome alike.

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Neural computation from cell to small networks

Stephane Binczak
LE2I UMR CNRS 5158, France
stbinc@u-bourgogne.fr
S. Jacquir, J.P. Gauthier and J.M. Bilbault

Neural networks are fascinating physical objects due to their ability to process information. There are several ways of understanding the dynamical mechanisms underlying neural computation. One of them consists in a multi-scale approach so that one distinguishes different kinds of processing, from the cellular level to large assemblies of neurons. In this presentation, we focus on some of these processing at different levels using a reaction-diffusion model as a representation of the neuron, from the nerve membrane level to the small assembly description. Firstly, we propose an analytical study based on a projection of a gradient flow of energy allowing determining the required energy needed for a neuron to fire. An application of these results concerns the role of the coupling parameter of electric synapses. Then, we present some results on the role of the geometry of the nerve fibers, and especially on the ephaptic coupling between them. Finally, we conclude on a small network system, enlightening the role of plasticity on phase computing.

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Computation in olfactory neuronal networks beyond synchronization

Markus Christen
Institute of Neuroinformatics, University/ETH Zurich, Switzerland
markus@ini.phys.ethz.ch
Alister Nicol, Keith Kendrick, Thomas Ott and Ruedi Stoop

It has been suggested that odor encoding in olfactory systems occurs by synchronized firing in neuronal populations. Neurons correlated in terms of the Lempel-Ziv distance of spike trains, and the sequential superparamagnetic clustering algorithm belong to the same cluster if they show similar, but not necessarily synchronous firing patterns. Using multi-electrode array recordings from the rat olfactory bulb, we have determined cluster incidence and stability in the neuronal network using both the Lempel-Ziv distance and a measure of synchronization. We find that ??? using both distance measures ??? neurons tend to be in the same clusters independent of the presence or absence of an odor, presumably reflecting the underlying neuronal connectivity that remains unchanged during short timescales. However, the stability of some clusters measured in the Lempel-Ziv paradigm changes significantly when an odor is presented to the olfactory neuronal network ??? an effect that is much less present in the synchronization paradigm. This indicates that neuronal clustering using the Lempel-Ziv distance may be a better approach to understand the computation performed in an olfactory neuronal network compared to synchronization.

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Information transfer and computation in *Drosophila* courtship behavior

Christian Heid
Institute of neuroinformatics ETHZ/UNIZH, Switzerland
mrheid@ini.phys.ethz.ch
R. Stoop

Courtship behavior is one standard example of genetically hardwired behaviors. Whereas normal male *Drosophila melanogaster* court females only, using advanced genetic techniques applied to the *fru* gene, it is now possible to generate males that only court males or court both genders, and females that court males or only court females. This provides hard evidence that gene information in addition to how living beings are built also defines to a considerable extent how they behave. Since *Drosophila* is under strong evolutionary pressure, pre-copulation courtship has been hypothesized to serve an information platform for assessing a potential partner's suitability for passing on genes. Here, we ask how this putative second aim can be reconciled within the genetical constraints. We provide evidence that a nontrivial symbolic language underlies *Drosophila* courtship behavior. This language allows normal male to express themselves within a large behavioral space, even leading the normal male to perform a contextual switch from male to female behavior, during the strongly unrewarding courtship situation with a fruitless male. We anticipate our assay and the developed methodological approach to be a starting point for systematic, detailed investigations of the relationship between genes and (in particular: courtship) behavior.

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Global Invariants for Variable-Mass Systems

Jim Howard
University of Colorado
jhoward@colorado.edu

We investigate the effect of mass loss on the invariants of systems having translational or rotational symmetry. These systems are nonhamiltonian in the physical momenta but, in the case of non-velocity-dependent potentials can be made formally hamiltonian by treating the velocities as canonical momenta. Applying Noether's theorem to the formal Hamiltonian then yields global invariants corresponding to its symmetries. For velocity-dependent potentials such as occur for motion in magnetic fields, an exact invariant is constructed from the (non-hamiltonian) vector field. The motion is thereby reduced from 3D to a 2D manifold with time-dependent effective potential parametrized by the conserved 'momentum'. The results are applied to single particle motion in an axisymmetric gravitational field, the time-dependent Kepler problem, and charged particle motion in linear and axisymmetric magnetic fields. Finally, we indicate how the results might be combined to describe the motion of charged dust grains about Saturn.

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Acoustic Source Separation by Atomic Signal Decomposition

Albert Kern
ETH Zürich, Switzerland
albert@ini.phys.ethz.ch
Th. Ott and R. Stoop

The separation of a mixed acoustic signal into its constituent sources is still a hard and challenging problem. We propose an approach to speech signal separation, which is based on a sparse time-frequency representation by local cosine packets. The separation is obtained by grouping (or: clustering) the individual local cosine packets to sets corresponding to the different sources. This grouping is performed by employing a criterion involving only the local frequency structure of the speech signal. In this way, it is possible to separate voiced speech segments. The grouping criterion can, however, be readily extended to include other, eg. time-related, speech features, such that successful speaker separation can be achieved in the general case. The sparse representation used leads to a very noise-robust separation method, which is crucial for real-world applications.

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Chaos and its control in applications to financial analysis

Alexander Loskutov
Moscow State University, Russia
loskutov@chaos.phys.msu.ru

All companies face the problem of optimization and further progress of the firm. Not in all cases this problem can be resolved successfully: We have to meet several difficulties. It is pretty often that the situation on the market is chaotic. In addition, it is necessarily to take into account to behavior of competitors and adapt the strategy in correspondence with the conditions on the market. We propose a possible way of such an optimization. We generalize analytic studies the problems related to suppression of chaos and non–feedback controlling chaotic motion. We develop analytic methods of the investigation of qualitative changes in chaotic dynamical systems under certain external periodic perturbations. We show that these methods allow to realize the stabilization of chaotic dynamic in some financial markets. Moreover, the used strategy leads to the increasing of the profit of firms and, thus, helps to build the strategy of the successful development.

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Repeated Patterns in Real-Time Behavior and Interactions: Definitions, Detection and Validation

Magnus S. Magnusson
University of Iceland
msm@hi.is

Discovering complex repeated interaction patterns, hidden to the naked eye, in real-time event-streams of human interactions, presupposes adequate pattern-type definitions. A pattern-type, called a t-pattern, and corresponding detection algorithms have been developed and used for the analysis of various kinds of human and animal behavior as well as for the detection of repeated multi-cell patterns of firing within populations of about 200 brain-cells registered simultaneously. The data is a set of time point series within the same interval, each series representing the beginning or end of a particular behavior by some agent. The t-pattern focuses on characteristics of well known behavioral patterns, that is, the involvement of a particular set of event-types occurring in a particular order and/or concurrently and with significantly similar time distances between consecutive pattern components. The detection algorithm uses bottom-up binary-tree detection of critical interval relationships between point series to connect primitives into patterns, while pattern completeness competition is used to deal with redundant detections and to evolve the most complete versions of each underlying pattern. Further structural types and algorithms have been defined on the basis of the t-pattern. Statistical validation relies on random (1 - 360) relative rotation (shifting) of the intact series.

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Phase-coupled neural networks: Architectures and computation

Stefan Martignoli
ETH Zürich, Switzerland
mstefan@ini.phys.ethz.ch
R. Stoop

We study discrete dynamical systems of coupled limit-cycle oscillators, where the pulse-like coupling is represented by an experimentally measurable phase response function. Starting from Arnold's description of phase-locking in mono-directionally coupled pair interaction, a general network algorithm is introduced, that allows the calculation of all 1d-Lyapunov exponents. By means of explicit return maps derived from the algorithm, it is demonstrated how the Arnold tongues are continuously transformed from the simpler to the more involved interaction topologies, providing a generalization of the phase-locking phenomena. Finally, laws for the propagation of perturbations are found for the feedforward and the recurrent network architecture types. By the application of the novel Stoop-measure for non-standard computation, computational classes emerging from the network's architecture can be identified.

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Message passing in loopy networks: From fixed points to vortex excitations

Thomas Ott
Institute of Neuroinformatics ETH Zurich, Switzerland
tott@ini.phys.ethz.ch
Norbert Stoop and Ruedi Stoop

Message passing in loopy networks: From fixed points to vortex excitations

Belief propagation (BP) has become a popular algorithm for solving a large variety of different inference problems. Based on the local exchange of messages, BP can be seen as a novel paradigm for distributed or network-based computation. If the underling network graph is loopy, there is, however, no guarantee that inference by means of BP is successful as BP may not converge. The calculation of the magnetization of paramagnetic Ising grids constitutes a typical inference problem on a loopy network. By means of this problem, we study interesting dynamical phenomena that BP yields beyond the convergence to stable fixed points. In particular, we point out and explain the phenomenon of critical slowing down and the existence of stable limit cycles that express a kind of vortex excitation within the network.

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Determining directionality of weak coupling between neuronal oscillators from time series: Phase dynamics modeling versus partial directed coherence

Dmitry Smirnov
Institute of RadioEngineering and Electronics of Russian Academy of Sciences, Saratov Branch, , Russia
smirnovda@info.sgu.ru
Bjoern Schelter, Matthias Winterhalder and Jens Timmer

Interaction between neuronal systems at the single cell level, as well as at the levels of mesoscopic neuronal populations and macroscopic brain structures, has been actively studied over the last decades. In particular, synchronization phenomena in neuronal populations have often been in the center of attention due to their relevance for the study of information processing in the brain, motor control, or pathological dynamical states such as epilepsy.

Detection of weak directional couplings in ensembles of neuronal oscillators from their time series is of comparable importance. We determine direction of coupling between neuronal oscillators by using a linear time series analysis technique (i.e. partial directed coherence) and a nonlinear one (i.e. phase dynamics modeling) for various spiking and bursting regimes and different types of coupling. Several exemplary neuronal models in the form of ordinary differential equations are considered, including FitzHugh-Nagumo, Hindmarsh-Rose, and Morris-Lecar systems. We formulate conditions of applicability and superiority for both analysis techniques. Phase dynamics modeling appears the most efficient analysis tool for studying the dynamics close to limit cycle behavior, while partial directed coherence is superior when the nonlinear structure is distorted by noise. The former analysis technique is less demanding to time series length and less robust to dynamical noise influence.

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Loopy belief propagation: Introduction, benefits, and pitfalls on Ising-like systems

Norbert Stoop
Department of Physics, ETH Zuerich, Switzerland
norbert@ini.phys.ethz.ch
Thomas Ott and Ruedi Stoop

Belief propagation can be considered as a method borrowed from how the brain processes information. The method substantially accelerates the convergence to the average values needed in the statistical approaches of complex spin systems. We discuss the behavior of belief propagation on loopy graphs and discuss results from a particular example, where we identify a critical slowing down of the algorithm due to a phase transition. For for lower temperatures, where the algorithm does no longer necessarily converge, for particular initial conditions a strange behavior of the algorithm emerges, which we propose to interpret as a fractal basin boundary problem.

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Neocortex minimizes its total connection length

Ruedi Stoop
Insitute of Neuroinformatics ETHZ/UNIZH, Switzerland
ruedi@ini.phys.ethz.ch
Clemens Wagner

We study in close-to-biology neural networks, synchronizability and information propagation speed, as a function of their topology. Starting from the experimental cortical evidence of columnar structures and an inverted power law distribution of long-range lateral connections, we designed a paradigm that systematically explores the architectural space, where node interaction is in terms of coupled-map-lattices of chaotic site maps. Criteria tested for are information propagation speed and synchronizability. The latter criterion guarantees the "binding" of distributed features towards single objects. Using this paradigm, we demonstrate that cortical bi-power law distributions significantly enhance information propagation speed and provide synchronization with a decreased number of connections ($\approx \frac{1}{2}$), leading for biologically realistic models to a significantly reduced total connection length (≈ 0.6). Moreover, the total connection length is also markedly shorter than that of a purely random-coupled network. This demonstrates that topology has a strong impact on the efficiency of neural networks and therefore, has computational significance. It also suggests that in the neocortical network, information propagation and synchronizability is optimized under the constraint of minimal total connection length, an aspect that has recently become a focus of interest for high-integration chip design.

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