Coupled oscillators and synchronization: From theory to data analysis
(Level: introductory (morning sessions)/ intermediate (afternoon sessions))

SUMMARY:
The course presents data analysis techniques based on the theory of coupled oscillators and aimed at reconstruction of the network structure and inference of nodes properties from observations.
The approach assumes that the multi-variate time series under study are outputs of weakly-coupled self-sustained oscillators and that the signals are appropriate for phase estimation. Therefore, the course will begin with a short introduction into the theory of interacting oscillators and their synchronization. We will discuss effects of phase and frequency locking and illustrate them with numerous examples. Next, we will discuss how this ideas can be used in data analysis.
The main idea is to infer a model for phase dynamics of the observed network. Hence, the first step is to estimate phases from time series, and this step will be discussed in details. Then we will proceed with an analysis of the phase model with the goal to obtain the strength of directed links and infer the network structure. Thus, our technique represents an approach to the connectivity problem, relevant for physiology, neuroscience, and other fields. We demonstrate that our technique provides effective phase connectivity which is close, though not identical to the structural one. However, for weak coupling we achieve a good separation between existing and non-existing connections. We also discuss how the frequencies and phase response curves of interacting units can be estimated. Next, we extend the approach to cover the case of pulse-coupled neuron-like units, where only times of spikes can be registered, so that the data represent point processes. We will also demonstrate how the inferred phase model can predict synchronization domains in experiments.

SYLLABUS:
1. Self-sustained oscillator. Forced and coupled oscillators, phase and frequency locking, synchronization domains. Model of phase dynamics.
2. Phase and its estimation from data. Hilbert Transform. Phase vs angle variable.
3. Strength of interaction. Synchronization indices (phase locking values).
4. Direction of interaction. Reconstruction and analysis of phase model for two interacting units.
5. Networks, structural and effective connectivity. Triplet analysis, true and spurious connections.

6. An example: cardio-respiratory interaction.
7. Case of pulse coupled oscillators.
8. Properties of nodes: natural frequencies, phase response curves.

REFERENCES:

A. Pikovsky, M. Rosenblum, and J. Kurths,
Synchronization. A Universal Concept in Nonlinear Sciences,
Cambridge University Press, 2001.
(Basic theory, also for non-physicists, and basics of data analysis)

B. Kralemann, M. Frühwirth, A. Pikovsky, M. Rosenblum, T. Kenner, J. Schaefer, and M. Moser, In vivo cardiac phase response curve elucidates human respiratory heart rate variability, Nature Communications, 4, p. 2418, 2013

B. Kralemann, A. Pikovsky, and M. Rosenblum,
Reconstructing effective phase connectivity of oscillator networks from observations,
New Journal of Physics, 16, 085013, 2014

R. Cestnik and M. Rosenblum,
Inferring the phase response curve from observation of a continuously perturbed oscillator,
Scientific Reports 8, 13606, 2018

PRE-REQUISITES:
Basic knowledge of calculus and minimal knowlewdge of differential equations.

SHORT BIO:
MICHAEL ROSENBLUM has been a research scientist and Professor in the Department of Physics and Astronomy, University of Potsdam, Germany, since 1997.

His main research areas are nonlinear dynamics, synchronization theory, and time series analysis, with application to biological systems. The most important results include description of phase synchronization of chaotic systems, analysis of complex collective dynamics in large networks of interacting oscillators, development of feedback techniques for control of collective synchrony in neuronal networks (as a model of deep brain stimulation of Parkinsonian patients), methods for reconstruction of oscillatory networks from observations, application of these methods to analysis of cardio-respiratory interaction in humans.

Michael Rosenblum studied physics at Moscow Pedagogical University, and went on to work in the Mechanical Engineering Research Institute of the USSR Academy of Sciences, where he was awarded a PhD in physics and mathematics. He was a Humboldt fellow in the Max-Planck research group on nonlinear dynamics, and a visiting scientist at Boston University. He is a co-author (with A. Pikovsky and J. Kurths) of the book "Synchronization. A Universal Concept in Nonlinear Sciences", Cambridge University Press, 2001 and has published over 100 peer-review publications.

Michael Rosenblum served as a member of the Editorial Board of Physical Review E, terms 2008-2013. Since 2014 he is an Editor of Chaos: Int. J. of Nonlinear Science. He was named an American Physical Society Outstanding Referee for 2015.