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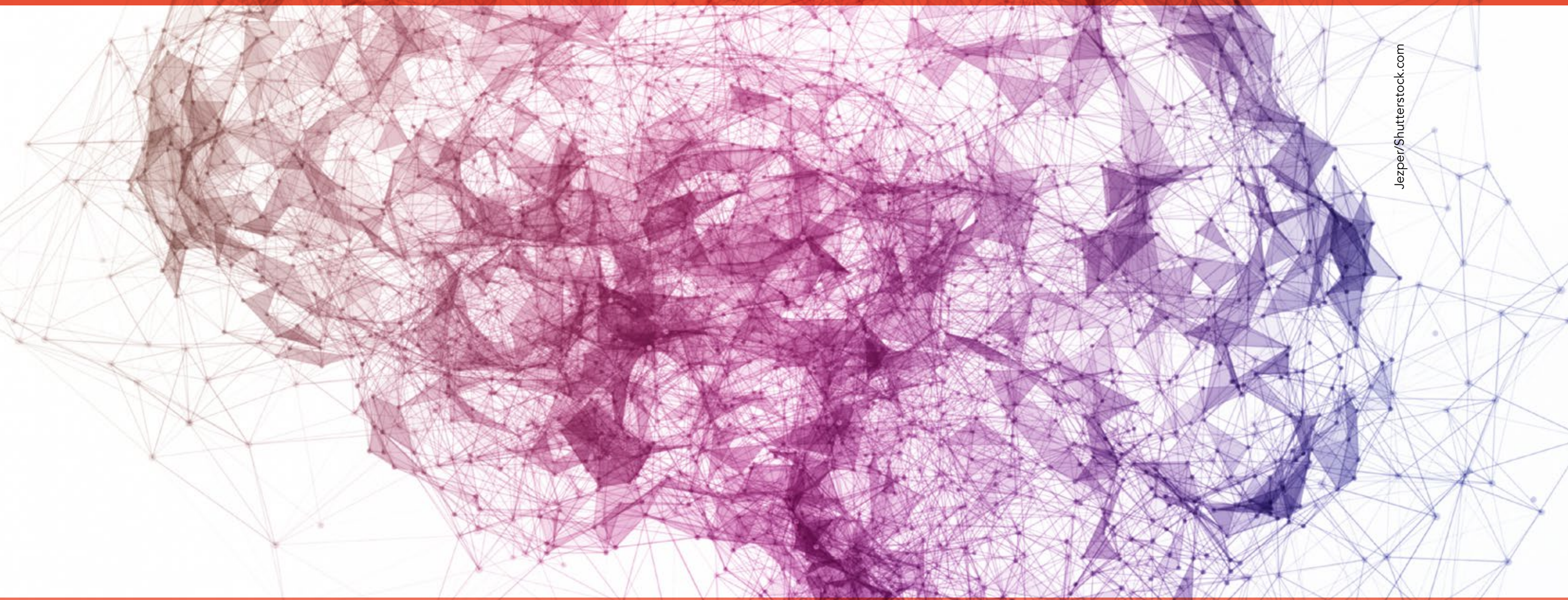

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Investigating partial synchronisation in complex dynamical networks

Detail

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Bio
Professor Zakharova received PhDs in physics and mathematics at Saratov State University (Russia) in 2010 and in physics at the University of Potsdam (Germany) in 2012, as well as habilitation in physics at TU Berlin in 2019. Since 2019, she has been a visiting professor at TU Berlin and a head of the research group Nonlinear Dynamics in Complex Networks. She is a Principal Investigator at the Collaborative Research Center 910, leading a team on control and dynamics of multilayer networks.

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Collaborators
- Professor Igor Franović (University of Belgrade)
- Professor Galina Strelkova (Saratov State University)

Research Objectives

Anna Zakharova explores nonlinear dynamical systems, noise-induced dynamics, control of neural networks, synchronisation patterns in dynamical networks, and stochastic effects in networks with time delay.

References

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Personal Response

What are some specific examples where excitability becomes relevant in real-world systems?

" Excitability may be seen as the main building block of 'physics of life', characterising local activity of neurons, cardiac, skeletal, and smooth muscle cells, and certain endocrine cells, like the pancreatic β-cells releasing insulin. "

Investigating partial synchronisation in complex dynamical networks

Synchronisation is a key feature of many complex dynamical systems, featuring networks of coupled oscillating elements. Yet as researchers discovered just two decades ago, a rich variety of complex spatio-temporal behaviours can arise during the transition between the states of complete synchrony and asynchrony. The most prominent example is provided by 'chimera' states: a pattern containing spatially co-existing regions of synchronisation and desynchronisation. Through over a decade of cutting-edge research, Professor Anna Zakharova at TU Berlin, Germany, has become a leading expert in these patterns, and their relevance in the diverse fields of neuroscience and neural networks.

Synchronisation is a fundamental emergent phenomenon in complex systems: it arises when multiple oscillating components adjust their rhythms due to interaction. As a simple example, consider a pair of synchronised swinging pendulums that would either reach the lowest points of their respective swings at exactly the same time, or after a constant delay. In reality, synchronisation in most natural systems is far more complex than this, and must be mathematically addressed through the language of 'nonlinear' dynamics. Nonlinear dynamics enables the description of systems where a simple superposition principle fails such that their output is not proportional to any changes of their input.

These behaviours are far more complex to study – but as Professor Anna Zakharova at TU Berlin explains, they are essential to gaining an in-depth understanding of the world around us. 'Synchronisation is of great importance in many areas: ranging from physics and chemistry to biology, neuroscience, socioeconomic systems, climatology and engineering', she says. 'It is ubiquitous both in natural and man-made systems, since their organisation and performance mostly depends on how different components are able to synchronise.'

Yet even with a detailed understanding of how synchronisation can be described in nonlinear systems – which may potentially contain vast clusters of interacting oscillators – researchers still don't have a complete understanding of how the phenomenon evolves, both spatially and temporally. For instance, synchronisation may only be transient and over time decay into a state of

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The states featuring coexistence of spatially coherent and incoherent regions are named 'chimera' states after the hybrid fire-breathing monster from Greek mythology: part lion, part goat, and part snake.

desynchronisation; or in some cases, synchrony may become localised rather than global, resulting in more exotic patterns of 'partial' synchronisation. This behaviour introduces yet another layer of complexity to the problem – but for Zakharova and her colleagues, the challenges it presents are by no means insurmountable.

SYNCHRONISATION IN THE BRAIN

One of the most important systems where different modalities of synchronisation matter most is the human brain. As the most complex dynamical system known to us, the brain is made up of about 86 billion neurons connected by thousands more synapses – with each neuron emitting oscillating electrical signals in response to signals they have received. As Zakharova describes, 'a metastable synchronisation between the oscillations in these signals at different layers of brain organisation are often the key to many of the brain's fundamental operations'.

'While the brain's rest state is asynchronous, the synchronisation of neurons is believed to play a crucial role in the context of cognitive functions, such as attention, perception and learning', she says. 'It is also vital to understanding brain disorders, such as epileptic seizures or Parkinson's disease.' In such cases, massive synchronisation events can cause catastrophic consequences, making it crucial for neuroscientists to understand the mechanisms which trigger them, allowing one to avoid their onset or to regain desynchronisation in a controlled way.

Synchronisation is of great importance in many areas: ranging from physics and chemistry to biology, neuroscience, socioeconomic systems, climatology and engineering.

This need is reflected in a wide range of scientific scenarios, in which nonlinear systems can undergo a broad spectrum of transitions between the states of complete synchrony and asynchrony. Through her research, Zakharova aims to gain complete theoretical knowledge of the underlying states and the mechanisms responsible for triggering them. Intriguingly, the story of this broad line of research only began in the relatively recent past.

CHIMERA AND SOLITARY STATES

In 2002, physicists Yoshiki Kuramoto and Dorjsuren Battogtokh were studying a computer-simulated system represented by a ring of *identical* phase

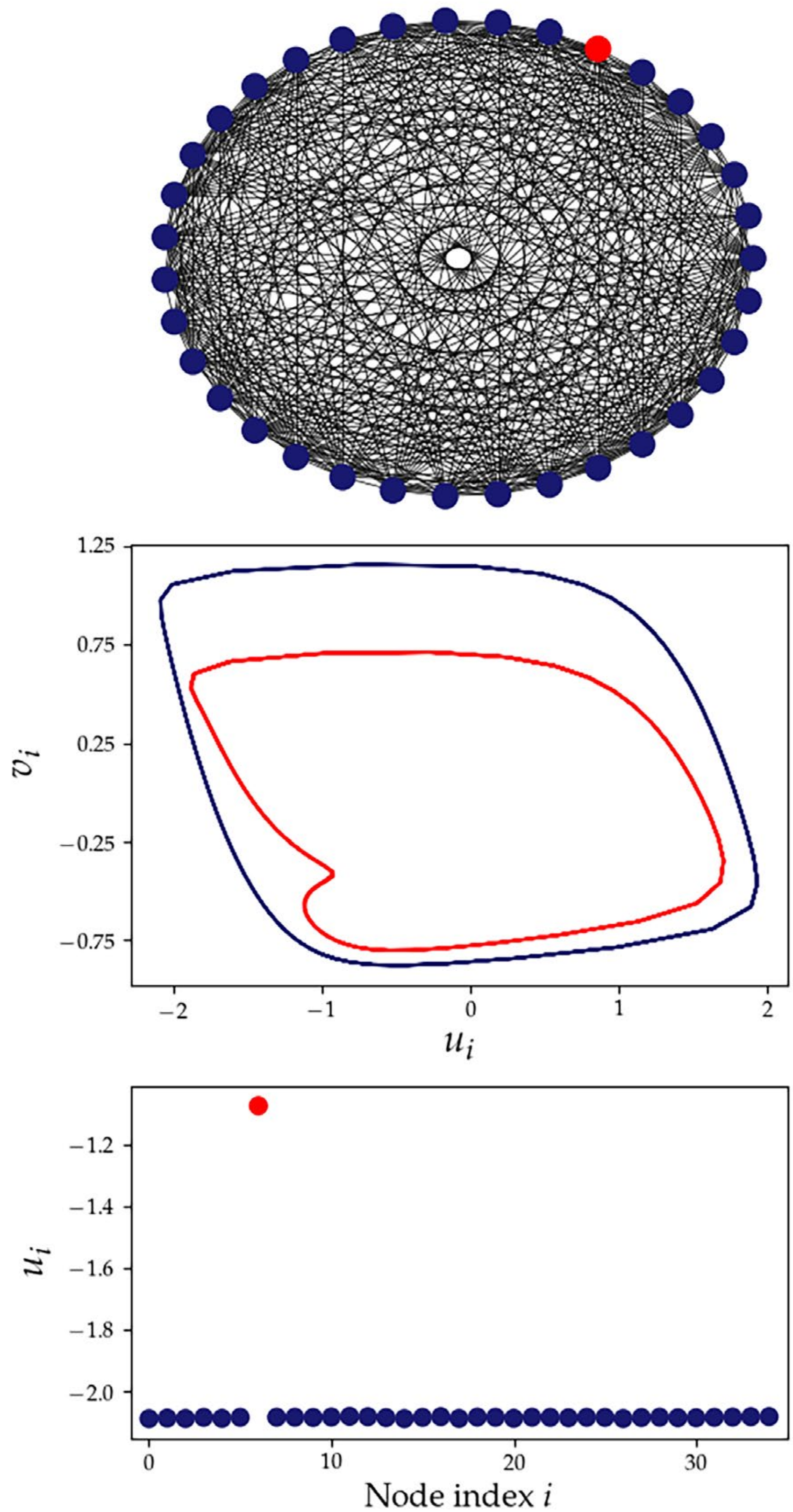


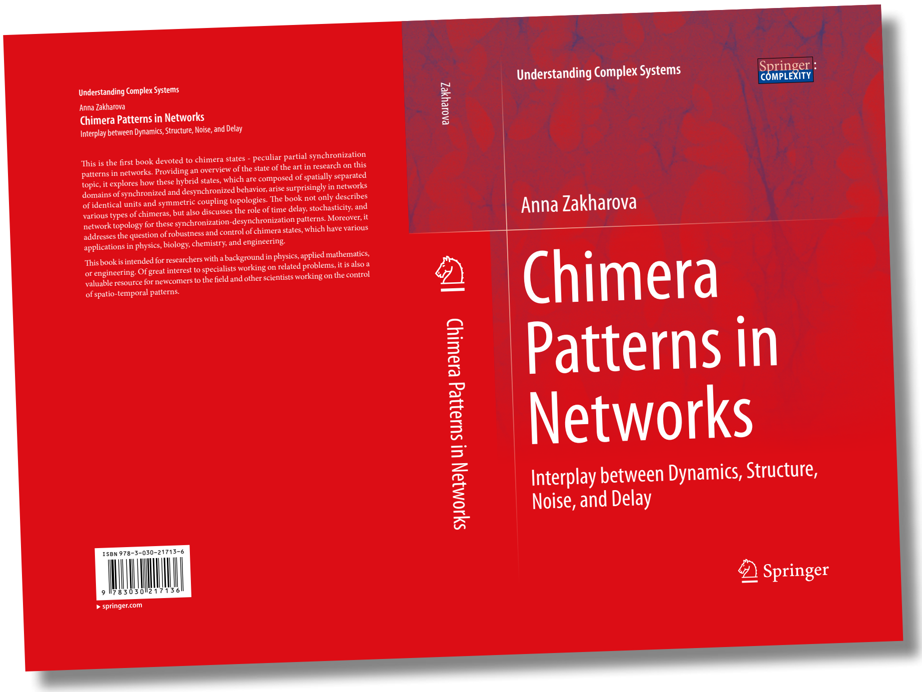
Figure 1. Solitary state in a network of coupled neural oscillators: the synchronised cluster (blue) and the solitary node (red). An Erdős–Rényi network with 35 nodes (top); Phase portrait (middle); Snapshot of the phase variable u_i for each FitzHugh-Nagumo oscillator (bottom). *Provided by Leonhard Schülen PhD student in Zakharova's lab.*

oscillators, interacting by nonlocal *symmetrical* couplings containing a uniform parameter to interpolate between attraction and repulsion. Such a system is the simplest possible environment for visualising the evolving nature of dynamical states. As they analysed their virtual system, the duo made a remarkable discovery: close to the repulsive regime, for specially prepared initial conditions the ring spontaneously split into a coherent region of synchronised oscillators and an incoherent/desynchronised region where the oscillators were drifting with different average frequencies. Such incongruous regions were strangely able to stably coexist with each other.

The states featuring such coexistence of spatially coherent and incoherent regions were later named 'chimera' states after the hybrid fire-breathing monster from Greek mythology: part lion, part goat, and part snake. Building on this initial research, Zakharova and her colleagues studied a computer-simulated ring of interacting neuronal oscillators to reveal another interesting form of partial synchronisation, called a 'solitary' state. Here, isolated oscillators can spontaneously unlock from the synchronised background (see Figure 1).

Chimeras and solitary states can be distinguished by the position in space at which the oscillators unlock from the synchronised cluster. 'In the case of chimera states, coexisting domains of synchronised and desynchronised behaviour are spatially localised,' Zakharova explains. 'For solitary states, on the contrary, it is typical that individual oscillators split off the synchronous cluster at random positions in space.'

Kuramoto and Battogtokh's discovery prompted a wave of interest in the nonlinear dynamics community and beyond. Overcoming the initial doubts on robustness of chimeras due to the need for specific initial conditions, the first lab experiments confirming observation of chimera states were reported a decade after their theoretical discovery. Chimeras were found in a large variety of settings: in optical light modulators and chemical oscillators, mechanical and optoelectronic



Drawing from over a decade of cutting-edge research, Zakharova's findings are continuing to expand researchers' understanding of chimera and solitary states.

oscillators, electrochemical systems and electronic circuits, to name but a few. Chimeras were also suggested to provide a dynamical background for phenomena outside laboratory, like power blackouts, diverse opinion trends in human society, heart ventricular fibrillation, and epileptic seizures. Despite the baffling nature of the pair's findings, researchers were soon able to develop robust mathematical descriptions of chimera and solitary states, and embody their complexity in ways that few other fields of physics can today.

DIFFERENT TRIGGERING MECHANISMS

Chimera states are now known to display a plethora of fascinating dynamics: influenced by factors including the dynamical heterogeneity of nonlinear systems; coupling delays; interaction patterns that arise within complex networks; and the coupling strength by which pairs of oscillators interact with each other. Much less is known about the ingredients relevant for onset of solitary states.

Both types of states can emerge by widely different mechanisms. 'Solitary states involve a soft onset of incoherence, since the oscillators are leaving the coherent cluster gradually', Zakharova describes. 'Chimera states typically emerge from coherence by a sharp transition, since the incipient incoherent domain immediately develops a finite and often large size.' Intriguingly, one and the same dynamical system can exhibit both types of states.

IMPLICATIONS FOR NEURAL NETWORKS

A specific feature of neural systems is that their elementary units, the neurons, are typically not intrinsic oscillators, but are rather excitable systems that act as nonlinear threshold-like elements. Excitability implies that in the absence of stimulations, neurons lie at a linearly stable rest state, but a sufficiently strong stimulation may trigger an oscillation corresponding to a neuronal spike. In their latest research, Zakharova and her collaborators have turned their attention to the emergence of complex patterns in 'excitable' systems. In contrast to systems of interacting oscillators, coupled excitable systems necessarily require repulsive interactions to manifest interesting collective phenomena. Moreover, in coupled excitable systems we see a different face of chimera patterns: for instance, their coherent part is typically stationary rather than oscillating. Currently, we are witnessing the emergence of exciting first glimpses on the mechanisms giving rise to chimera and solitary patterns in coupled excitable systems, including neural networks. Some of these may even contest the classical views, like those on soft vs sharp transition to incoherence, developed for systems of coupled oscillators. Understanding of the dynamical background of such states may likely give us a completely new insight on how to avoid certain undesired brain conditions, or allow us to comprehend some aspects of cognition. In particular, inducing solitary states may be a first step to breaking massive synchronisation associated with brain disorders, like epileptic seizures or Parkinson's disease, while certain states associated with chimeras, called neuronal bumps, may play a role in short-term memory and representation of spatial orientation in the head-direction cells that underlie our sense of direction.

IMPARTING KNOWLEDGE OF PARTIAL SYNCHRONISATION

Drawing from over a decade of cutting-edge research, Zakharova's findings are continuing to expand researchers' understanding of chimera and solitary states. At the same time, she has imparted her own expert knowledge on the subject through the first dedicated book on chimera states, published in 2020. Titled *Chimera Patterns in Networks: Interplay between Dynamics, Structure, Noise, and Delay*, the book provides a vital resource both for senior and upcoming researchers in the field, as they seek to understand the full significance of partially synchronised dynamical systems.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