Team develops a solution for temporal asymmetry

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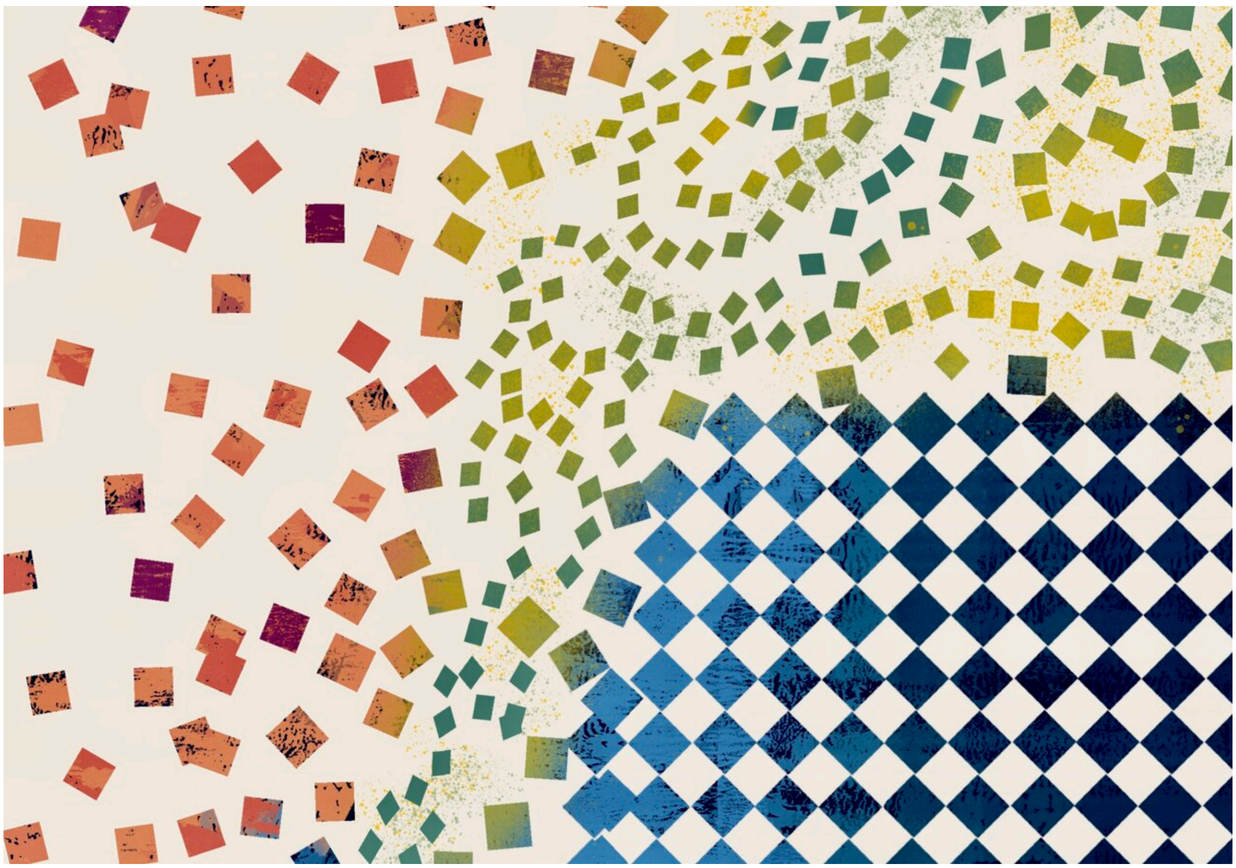

Representation of the time-asymmetry in the heterogeneous network dynamics unveiled by the study. Credit: KyotoU/Robin Hoshino

Life, from the perspective of thermodynamics, is a system out of equilibrium, resisting tendencies towards increasing their levels of disorder. In such a state, the dynamics are irreversible over time. This link between the tendency toward disorder and irreversibility is expressed as the 'arrow of time' by the English physicist Arthur Eddington in 1927.

Now, an international team including researchers from Kyoto University, Hokkaido University, and the Basque Center for Applied Mathematics, has developed a solution for temporal asymmetry, furthering our understanding of the behavior of biological systems, machine learning, and AI tools.

"The study offers, for the first time, an exact mathematical solution of the temporal asymmetry—also known as entropy production—of nonequilibrium disordered Ising networks," says co-author Miguel Aguilera of the Basque Center for Applied Mathematics.

The researchers focused on a prototype of large-scale complex networks called the Ising model, a tool used to study recurrently connected neurons. When connections between neurons are symmetric, the Ising model is in a state of equilibrium and presents complex disordered states called spin glasses. The mathematical solution of this state led to the award of the 2021 Nobel Prize in physics to Giorgio Parisi.

Unlike in living systems, however, spin crystals are in equilibrium and their dynamics are time-reversible. The researchers instead worked on the time-irreversible Ising dynamics caused by asymmetric connections between neurons.

The exact solutions obtained serve as benchmarks for developing approximate methods for learning artificial neural networks. The development of learning methods used in multiple phases may advance machine learning studies.

"The Ising model underpins recent advances in deep learning and generative artificial neural networks. So, understanding its behavior offers critical insights into both biological and artificial intelligence in general," added Hideaki Shimazaki at KyotoU's Graduate School of Informatics.

"Our findings are the result of an exciting collaboration involving insights from physics, neuroscience and mathematical modeling," remarked Aguilera. "The multidisciplinary approach has opened the door to novel ways to understand the organization of large-scale complex networks and perhaps decipher the thermodynamic arrow of time."

The research is published in the journal *Nature Communications*.

More information: Miguel Aguilera et al, Nonequilibrium thermodynamics of the asymmetric Sherrington-Kirkpatrick model, *Nature Communications* (2023). DOI: 10.1038/s41467-023-39107-y

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