Can deep learning techniques predict sudden state transitions in nonlinear dynamical systems?

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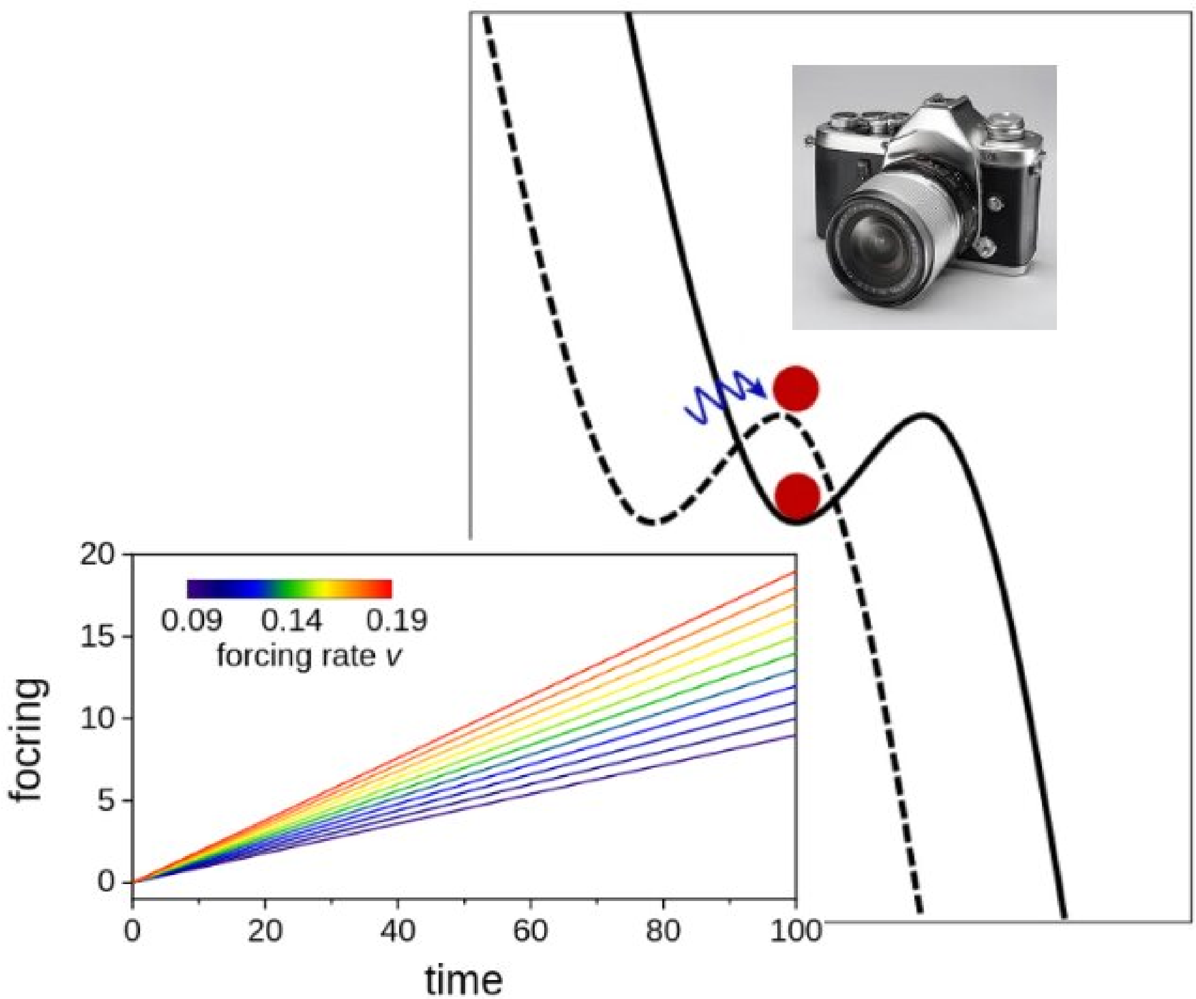

If the time-varying forcing changes too fast, it can cause a system to lose its previous stability. Deep learning can help to foresee the underlying tipping probability. Credit: Huang et al.

Nonlinear dynamical systems are systems that can undergo sudden shifts not due to changes in their state or stability, but in response to the rate at which external conditions or parameters change. These sudden shifts, known as noise-induced and rate-induced tipping, can make predicting how the systems will shift over time more challenging.

Researchers at the Technical University of Munich, the Potsdam Institute for Climate Impact Research and the University of Exeter carried out a study exploring the potential of deep learning techniques for predicting noise-induced and rate-induced tipping. Their paper, published in *Nature Machine Intelligence*, suggests that sudden shifts in nonlinear dynamical systems, such as climate change, could be reliably predicted using artificial intelligence (AI).

"Our team and our long-term research scope focus on Earth system tipping points, with the aim of figuring out the background dynamics, uncertainty, practical prediction and socioeconomic impacts of tipping points," Yu Huang, first author of the paper, told Tech Xplore.

"Scientists from climate, ecology, physics, math and dynamical systems have devoted a lot of great contributions to this field. So far, there are many valid prediction theories and tools for Bifurcation-induced tipping. However, another two kinds of tipping, noise-induced tipping and rate-induced tipping, also pose crucial risks and large uncertainty to the instability of climatic and ecological systems."

Noise-induced tipping and rate-induced tipping are two types of shifts observed in nonlinear dynamical systems, which are associated with random fluctuations in the environment or the rate at which an external parameter changes, respectively.

In the context of climate change, for instance, noise-induced tipping could have effects on ecosystems caused by random weather patterns, while rate-induced tipping could be linked to the increase in the rate at which temperatures are increasing.

Reliably predicting these two types of tipping has so far proved challenging. A key goal of Huang and his colleagues was to determine whether noise-induced and rate-induced shifts could be accurately predicted using machine learning algorithms.

"By collecting a lot of samples and closely examining the raw data before rate-induced tipping occurs, we can already visually observe some subtle changes in the data's statistical probability distributions," explained Huang. "However, this observation experience is from the ensemble samples. Can we directly use it on a single sample to infer if rate-induced tipping will happen? Deep learning gives us this chance."

Huang and his colleagues trained a deep learning model on time series data showing changes in various nonlinear dynamical systems with different underlying dynamics. During training, the model gradually learned to infer the probability of rate-induced tipping occurring from a given sequence of events.

"So far there was no predictive theory for rate-induced and noise-induced tipping, this study introduces deep learning as an effective tool for these tipping events," said Huang.

"Additionally, we find that the prediction effectiveness is independent of the specific neural network architectures, the good transferability can work across different forcing rates and dynamical systems, and the explainable AI can help us to discover tipping point fingerprints from the data."

Earlier studies had already demonstrated the potential of deep-learning for predicting bifurcation-induced tipping. This is a sudden shift in dynamical systems induced by bifurcation (i.e., changes in a system's equilibrium or periodic behavior when an internal parameter crosses a critical threshold).

"Along with earlier studies finding that deep learning works well for predicting bifurcation-induced tipping, our new findings inspire us a lot," said Huang. "They imply that it is wishful thinking to obtain a comprehensive early warning indicator for different kinds of tipping and a critical threshold across forcing value and forcing rate."

The recent work by this team of researchers could soon inspire the development of more deep learning models to predict rate- and noise-induced tipping, which could prove useful for forecasting climatic and environmental changes. Meanwhile, Huang and his colleagues are conducting new research focusing on three different topics.

Firstly, they are trying to improve the deep learning model they developed and train it on more comprehensive datasets. This could facilitate its use as a tool to reliably predict the three main types of tipping observed in nonlinear dynamical systems.

"The second research direction we are exploring focuses on the explainable AI's discovery of precursor signals for tipping points, with the aim of understanding the underlying physical and mathematical mechanisms," added Huang.

"This could be helpful to establish predictive theory for rate-induced and noise-induced tipping. The third future research direction is rooted in an open question. Our study used deep learning to predict the system's tipping probability before the tipping happens. As a further step, it could also be interesting to predict the time-evolutionary trajectory of a system before and after a tipping point, so that we can predict the tipping trajectory of rate-induced tipping, instead of the tipping probability."

More information: Yu Huang et al, Deep learning for predicting rate-induced tipping, *Nature Machine Intelligence* (2024). DOI: 10.1038/s42256-024-00937-0.

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