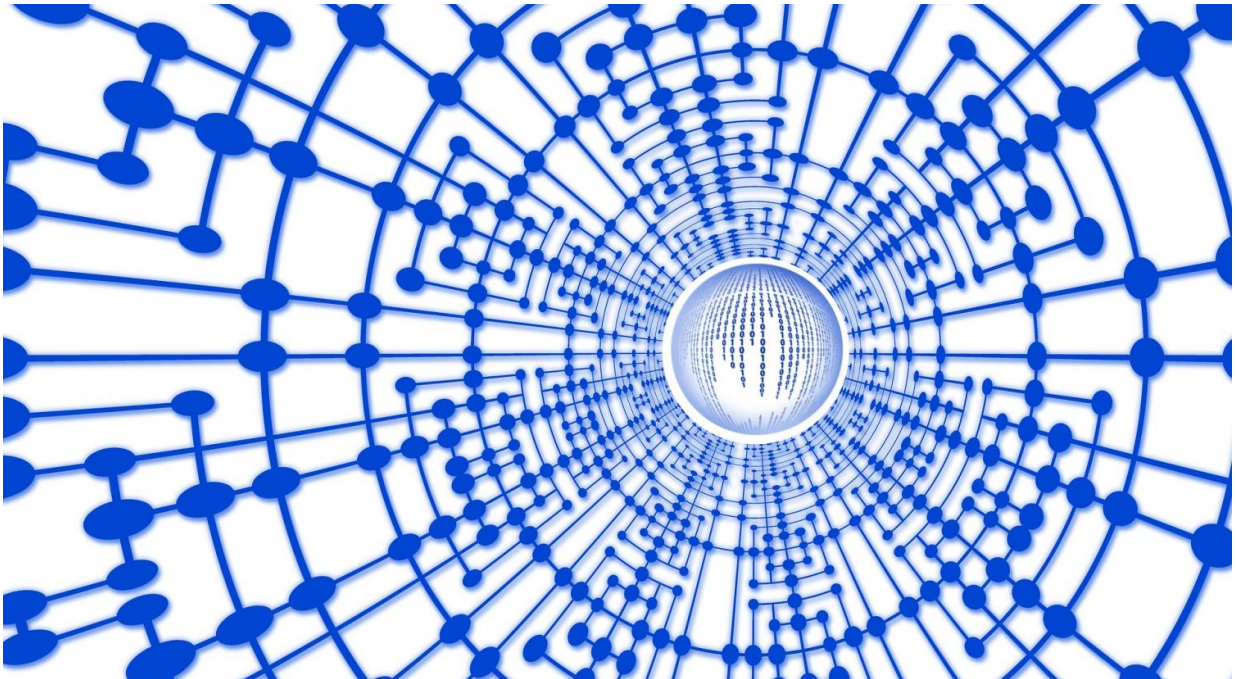# New technique spots warning signs of extreme events

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Credit: CC0 Public Domain

Many extreme events—from a rogue wave that rises up from calm waters, to an instability inside a gas turbine, to the sudden extinction of a previously hardy wildlife species—seem to occur without warning. It's often impossible to predict when such bursts of instability will strike, particularly in systems with a complex and ever-changing mix of players and pieces.

Now engineers at MIT have devised a framework for identifying key patterns that precede an extreme event. The framework can be applied to a wide range of complicated, multidimensional systems to pick out the warning signs that are most likely to occur in the real world.

"Currently there is no method to explain when these extreme events occur," says Themistoklis Sapsis, associate professor of mechanical and ocean engineering at MIT. "We have applied this framework to turbulent fluid flows, which are the Holy Grail of extreme events. They're encountered in climate dynamics in the form of extreme rainfall, in engineering fluid flows such as stresses around an airfoil, and acoustic instabilities inside gas turbines. If we can predict the occurrence of these extreme events, hopefully we can apply some control strategies to avoid them."

Sapsis and MIT postdoc Mohammad Farazmand have published their results today in the journal *Science Advances*.

Looking past exotic warnings

In predicting extreme events in complex systems, scientists have typically attempted to solve sets of dynamical equations—incredibly complex mathematical formulas that, once solved, can predict the state of a complex system over time.

Researchers can plug into such equations a set of initial conditions, or values for certain variables, and solve the equations under those conditions. If the result yields a state that is considered an extreme event in the system, scientists can conclude that those initial conditions must be a precursor, or warning sign.

Dynamical equations are formulated based on a system's underlying physics. But Sapsis says that the physics governing many complex

systems are often not well-understood and they contain important model errors. Relying on these equations to predict the state of such systems would therefore be unrealistic.

Even in systems where the physics are well-characterized, he says there is a huge number of initial conditions one could plug into associated equations, to yield an equally huge number of possible outcomes. What's more, the equations, based on theory, might successfully identify an enormous number of precursors for extreme events, but those precursors, or initial states, might not all occur in the real world.

"If we just blindly take the equations and start looking for initial states that evolve to extreme events, there is a high probability we will end up with initial states that are very exotic, meaning they will never ever occur for any practical situation," Sapsis says. "So equations contain more information than we really need."

Aside from equations, scientists have also looked through available data on real-world systems to pick out characteristic warning patterns. But by their nature, extreme events occur only rarely, and Sapsis says if one were to rely solely on data, they would need an enormous amount of data, over a long period of time, to be able to identify precursors with any certainty.

Searching for hotspots

The researchers instead developed a general framework, in the form of a computer algorithm, that combines both equations and available data to identify the precursors of extreme events that are most likely to occur in the real world.

"We are looking at the equations for possible states that have very high growth rates and become extreme events, but they are also consistent

with data, telling us whether this state has any likelihood of occurring, or if it's something so exotic that, yes, it will lead to an extreme event, but the probability of it occurring is basically zero," Sapsis says.

In this way, the framework acts as a sort of sieve, capturing only those precursors that one would actually see in a real-world system.

Sapsis and Farazmand tested their approach on a model of turbulent fluid flow—a prototype system of fluid dynamics that describes a chaotic fluid, such as a plume of cigarette smoke, the airflow around a jet engine, ocean and atmospheric circulation, and even the flow of blood through heart valves and arteries.

"We used the equations describing the system, as well as some basic properties of the system, expressed through data obtained from a small number of numerical simulations, and we came up with precursors which are characteristic signals, telling us before the extreme event starts to develop, that there is something coming up," Sapsis explains.

They then performed a simulation of a turbulent fluid flow and looked for the precursors that their method predicted. They found the precursors developed into extreme events between 75 and 99 percent of the time, depending on the complexity of the fluid flow they were simulating.

Sapsis says the framework is generalizable enough to apply to a wide range of systems in which extreme events may occur. He plans to apply the technique to scenarios in which fluid flows against a boundary or wall. Examples, he says, are air flows around jet planes, and ocean currents against oil risers.

"This happens in random places around the world, and the question is being able to predict where these vortices or hotspots of extreme events

will occur," Sapsis says. "If you can predict where these things occur, maybe you can develop some control techniques to suppress them."

 More information: "A variational approach to probing extreme events in turbulent dynamical systems" *Science Advances* (2017). advances.sciencemag.org/content/3/9/e1701533

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