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The butterfly effect is a real phenomenon—but not how you think

The popular concept has been depicted in everything from film to social media testimonials, but the real science behind the butterfly effect can help scientists predict the future.

A monarch butterfly (*Dannaux plexippus*) flaps its wings in Piedra Herrada Sanctuary, Mexico. Might this start a chain of events that results in a tornado in Texas?
Photograph by Jaime Rojo

By
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In 1961, MIT meteorologist Edward Lorenz was inputting numbers into a weather prediction program. His model was based on a dozen variables, the value of one being .506127. When he ran the model again, he rounded that number to .506, then left the room to grab a coffee. When he came back, he discovered this tiny change had resulted in a dramatically different weather prediction.

When presenting his resultant groundbreaking model of chaos and the potential of extreme chaotic unpredictability at the 1972 meeting of the American Association for the Advancement of Science (AAAS), Lorenz posed the question: "Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?"

Richard A. Anthes, former president of the University Corporation for Atmospheric Research in Boulder, Colorado (now president emeritus), says Lorenz was illustrating how, "in a system of apparently simple mathematical equations, an infinitesimal change in the initial position of the particle can cause huge changes in its future position—a tiny change now may lead to gigantic and unpredictable change in the future."

The chaotic motion of double pendulums illustrates how minute differences in initial conditions can become compounded over time until it produces an entirely unique and unpredictable result.

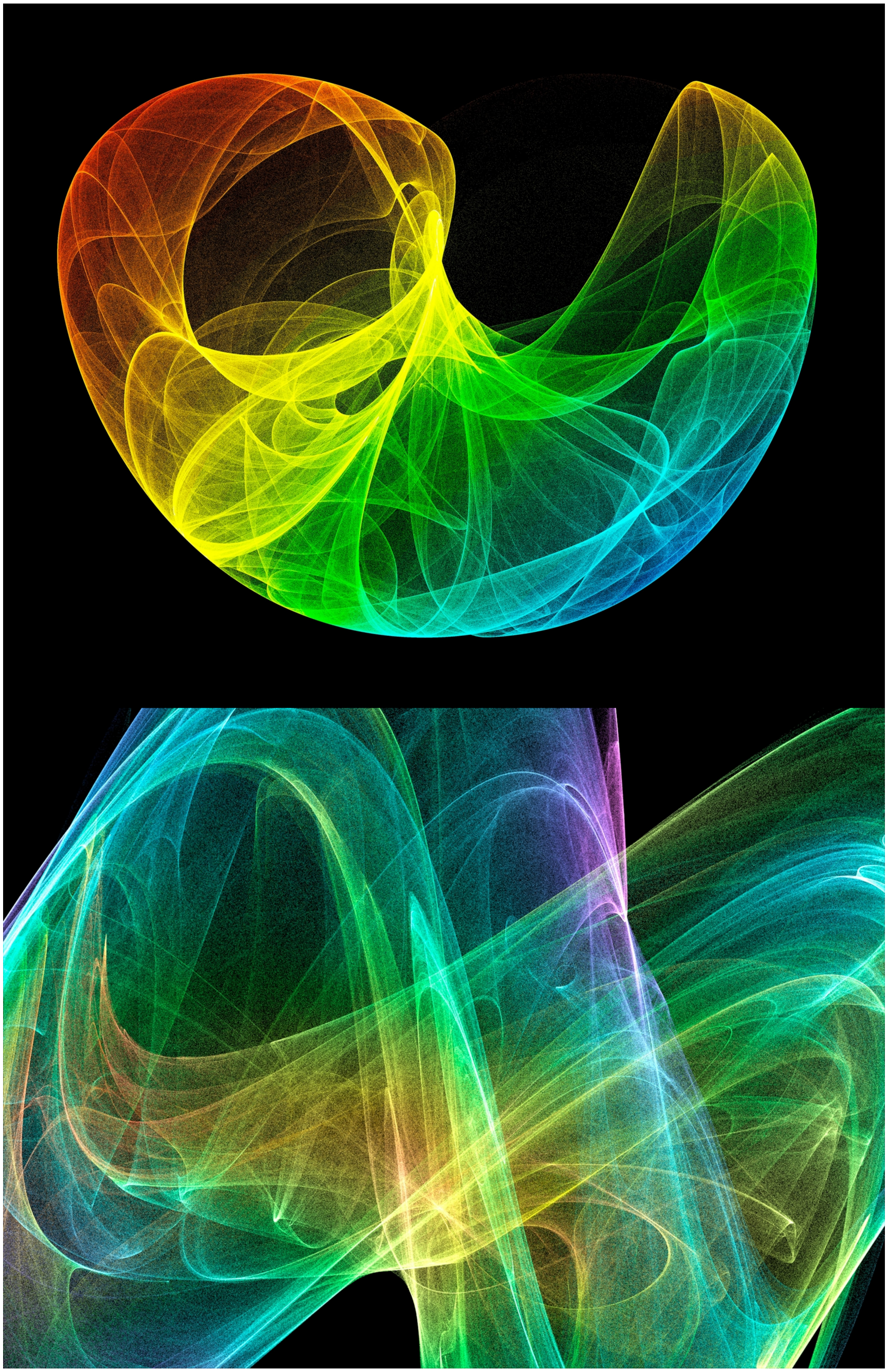
This analogy—that small, seemingly insignificant acts by individuals can lead to disruption or chaos in the future—so simply and beautifully rendered with Lorenz's captivating metaphor, captured the imaginations of scientists and the public alike.

The butterfly effect "disrupted science at a philosophical level, showing that modeling the future is only predictable to an extent, and that 'chaos,' as Lorenz put it, is always present but difficult to discern," explains Bo-Wen Shen, an associate professor of mathematics and statistics at San Diego State University who's written extensively about the butterfly effect. Shen thinks this is because the idea that even the slightest perturbations may have significant impacts "offers hope to individuals, encouraging them to take small actions that could have a profound and positive effect."

The concept has been the subject of films and was more recently a social media trend in which people shared their butterfly effect stories: seemingly random events—a car breaking down, a missed train, a broken shoe—that lead to significant moments in their life, such as meeting a future spouse or avoiding a bigger catastrophe.

These stories often misunderstand Lorenz's original concept and more accurately describe a coincidence.

While the butterfly effect may be prone to oversimplification in pop culture, scientists are still using the concept to predict how what we do in the present will change future.



Artwork of a Lorenz attractor, named after scientist Edward Lorenz. In particular, the Lorenz attractor is a set of chaotic solutions of the Lorenz system which, when plotted, resemble a butterfly or figure eight. Minute variations in the initial values of the variables would lead to

hugely divergent outcomes. For this phenomenon, of sensitivity to initial conditions, he coined the term butterfly effect.
Illustration by Alfred Pasieka, Science Photo Library (Top) (Left) and Illustration by Alfred Pasieka, Science Photo Library (Bottom) (Right)

Why the butterfly effect is the subject of scientific debate

The main disconnect around popular interpretations of the butterfly effect lies in the belief that the ability of a tiny perturbation to create an organized disturbance at large distances is a real phenomenon.

“[It] is a metaphor,” Shen insists, noting that leading experts on the subject recently agreed that it is a Schrödinger’s cat of an idea: never scientifically proven or disproven.

“The metaphorical definition of the butterfly effect is widely accepted as literally true. It is not,” asserts Roger Pielke Sr, professor emeritus of the department of atmospheric science at Colorado State University. “The bottom line, with respect to whether a butterfly flap can result in the development of a tornado thousands of kilometers away (or even locally), is that it cannot under any circumstances. The answer is a categorical NO.”

If you’re confused, don’t worry. Even experts don’t agree on what the concept truly means. *Physics Today* was home to a spirited back-and-forth of papers on the topic in 2024, between Shen’s team and Oxford University climate physics professor Tim Palmer, debating the nature of the butterfly effect and its implications.

Palmer believes that when detailing the butterfly effect, Lorenz was describing how weather is the culmination of seemingly independent atmospheric patterns collectively and momentarily changing the environment. In a 2017 Oxford podcast, he says to imagine weather like a set of Russian dolls: Within a 1,000-kilometer wide low pressure system are 100-kilometer thunderstorm clouds, and within those, sub clouds with turbulent eddies, and within those sub clouds, yet smaller turbulence eddies.

Palmer has his own ideas about how the butterfly effect should be defined and how it’s misunderstood, saying in a 2014 scientific article that “there are finite predictability horizons which cannot be extended by reducing uncertainty in initial conditions.”

Shen says the butterfly effect is best illustrated using this proverb-like folktale (first recorded by poet George Herbert in 1640):

“For want of a nail, the shoe was lost.

For want of a shoe, the horse was lost.

For want of a horse, the rider was lost.

For want of a rider, the battle was lost.

For want of a battle, the kingdom was lost.

And all for the want of a horseshoe nail."

"The verse suggests that any slight perturbation can eventually yield a substantial effect on numerical integrations," Shen notes. "Lorenz believed that the folklore better illustrated the simpler phenomenon of instability." The verse also reminds us that subsequent small events will not reverse the outcome.

A close up of a butterfly's wing. The butterfly effect has become a popular pop culture metaphor that describes how a seemingly small action can lead to a life-changing result.
Photograph by Konrad Wothe, Picture Press/Redux

Making sense of chaos

The butterfly effect has been instrumental in scientifically defining chaos.

"One extraordinary contribution by Prof. Lorenz is that his models and methods have provided foundations that have inspired numerous studies and further advanced our understanding of chaotic nature and limited predictability," says Shen.

Scientists have since discovered that chaotic systems—such as weather, the population growth of a single species, or even the flow of traffic—either produce single chaotic solutions that are seemingly random but actually just hypersensitive to their initial conditions, or coexisting chaotic and regular solutions. Minor changes may not always cause significant impacts, or their effects may be limited in the real world.

"Imagine a vast river flowing towards the ocean. The overall current of the river influences the movements of smaller eddies and swirls. Even though these smaller features might appear chaotic and unpredictable on their own, the larger-scale context provides a framework for understanding their behavior," explains Shen. "By observing these larger-scale weather patterns, we can gain more insight into how these smaller, more chaotic events might unfold."

Or as Anthes puts it, "not all butterflies make a difference."

According to Lorenz' theory, you can't measure the weather today meticulously enough to accurately predict the weather in the far future; the practical limit to weather prediction caps at a couple of weeks.

Shen wants to test those limits. He and his team have published papers using Lorenz' models and offered a new perspective on the dual nature of chaos and order in weather and climate.

Monarch butterflies at the Santuario El Rosario, Mexico. The butterfly effect was conceived as a meteorological concept, but the framework may help scientists model future climate outcomes. Photograph by Jaime Rojo, Nat Geo Image Collection

How the butterfly theory applies to a changing climate

While the main usefulness of the butterfly effect lies in weather prediction, it can also help scientists model climate change. Recently, researchers were hoping to use AI to help simulate the butterfly effect to improve weather predictions. Sadly, AI failed to simulate the butterfly effect. This doesn't negate the butterfly effect, it just tells us that AI cannot conceive of it.

The impact of Lorenz and his butterfly effect continues to unfold. Chaos theory has revolutionized various branches of physics, biology, engineering, economics, even social science. Anthes says Lorenz' model has had an enormous effect on all fields in which the future depends on the present.

"The concept of the butterfly effect applies to almost any complex system in which the future state depends on the present state … the atmosphere and oceans, climate, physics, biological systems including human health, and society in general including economics and political systems," says Anthes. "Seemingly small changes can have enormous and unpredictable, as well as unintended, consequences in the future."

In 2011, MIT opened a climate research institute named after Lorenz that funds scientific research without an obvious real-world application. This type of "pure research," as it's called, will help us learn about all the small actions that may be as consequential as the flap of a butterfly's wings.

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