In pop culture, we often use the phrase – *butterfly effect* – to express how tiny, insignificant changes can later have huge consequences, making the future unpredictable.[1] People in Vancouver always bring an umbrella with them even if the forecast says that it will not rain. Is it because the forecast likes to trick people? Absolutely not, the forecast has tried its best. This is because weather is extremely sensitive, as a small perturbations to the initial condition, such as a butterfly flapping its wings, will result in completely different outcomes. A metaphor for the *butterfly effect* on weather is that a butterfly flapping its wings in China can cause a hurricane in Texas.[2] Sensitive dynamical systems like the system of weather are called chaotic. The *Butterfly Effect* is an underlying principle of chaos,[2] and the science behind it really explains why we cannot predict the future, or in fact, we can't even predict with complete certainty.[1]

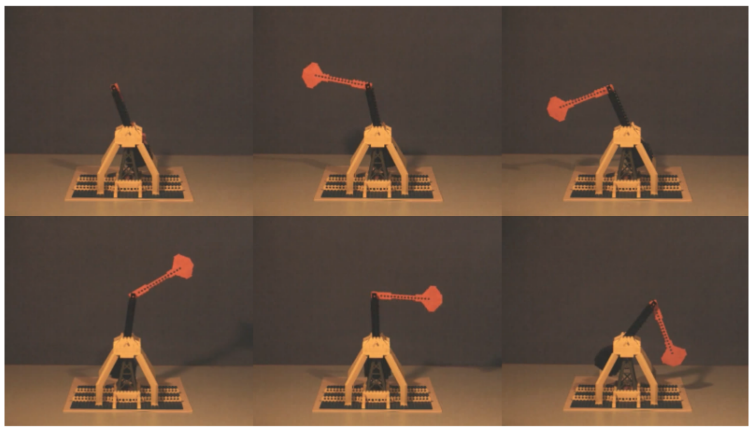

Figure 1: Double Pendulum: Drastic difference after a minute with the same initial condition[3]

Before we dive into the math behind chaotic systems and the *Butterfly Effect*, we need to understand the term *deterministic*. Here is a famous thought experiment: imagine there is a demon named Laplace who knows everything that has happened. It knows what current GPA you have at the University, and the precise location and momentum of every atom in the universe. By some calculations using the laws of classical mechanics, Laplace should also know everything's future values for any given time, even your GPA after graduation.[4] Then, predicting the weather should not be problematic at all, since the weather would be determined completely by the past. However, the assumptions of determinism were challenged when the mathematician, Edward Lorenz, had ran some simulations of weather of the Earth's atmosphere using initial condition data on a computer. He first submitted unrounded data, and wanted to redo the run to double-check the result. To save time, he input rounded initial condition data for a second run. Lorenz was stunned by the result; it was not even close to the first simulation. Only few decimals difference that is less than one part

[1] "The Science Behind the Butterfly Effect." YouTube, 6 Dec. 2019, https://www.youtube.com/watch?v=fDek6cYijxI.

[2] "Chaos Theory." Wikipedia, Wikimedia Foundation, 17 Mar. 2020, https://en.wikipedia.org/wiki/Chaos_theory.

[3] Picture source

[4] "Laplace's Demon." Wikipedia, Wikimedia Foundation, 7 Mar. 2020, https://en.wikipedia.org/wiki/Laplace's_demon.

in a thousand in the initial condition data simulates totally different weather! Lorenz re-ensured this phenomenon with a simpler model that had fewer equations, but the same thing happened again. A very small change in initial conditions creates a significantly different outcome. This is the fundamental idea of chaos.[5]

If we plot out the the equations that Lorenz used for the weather simulation along with a wide range of initial conditions, we will get the following beautiful, butterfly-like graph. Notice that none of the paths cross each other or form a loop (if you have read my previous essay, you would realize that it is a fractal).

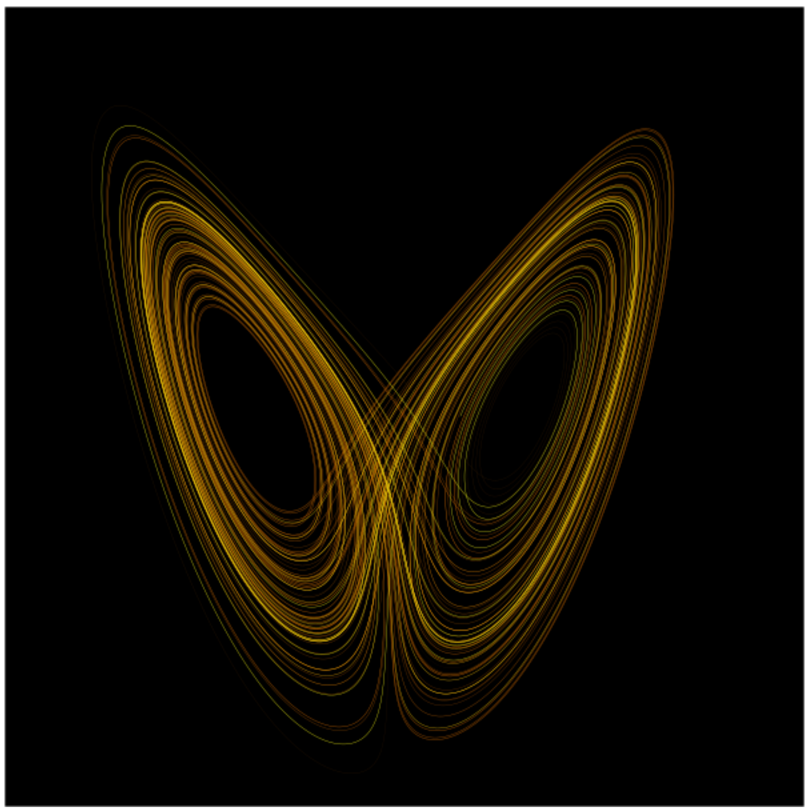

Figure 2: An Icon of Chaos Theory - The Lorenz Attractor[5]

If we can input the exact same initial condition each time, it will return the same result; in other words, the same loop of the path will be traced on the above graph. This might seem contradicting as this system, the computer simulation of weather, is both deterministic and unpredictable! In practice, we can never get the perfect precision of any initial condition that has infinite decimal places.[1] Since it is impossible to input the exact same initial condition every time, it makes the system of weather chaotic. This is why even with current technologies can create advanced artificial intelligence like Alpha Go, we still cannot forecast the weather a week advance. Studies have shown that by the eighth day, the prediction of weather is less accurate than by taking the average of the

[5] "Butterfly Effect." Wikipedia, Wikimedia Foundation, 16 Mar. 2020, https://en.wikipedia.org/wiki/Butterfly_effect.

historical temperature. Another example of a chaotic system is the solar system. The interactions between planets cause very complicated behaviour. In 10 to 15 million years, some planets may collide or moons may fly out of the solar system.[1]

Making predictions is less easy than what determinists would expect, at least when it comes to chaotic systems like weather and the solar system. There are many chaotic systems in the world that hinder us from predicting the future. Rounding error is one of the biggest challenges that we have to face. Maybe someone will be able to develop an accurate and efficient way to store data, including initial conditions perfectly, and then we might predict the future. But life might be boring if we were not living in a fog, finding our path in this world with non-predetermined events.