

Deterministic Chaos

Introduction

This is a project based on the subject of chaos theory. The aim of this project was to investigate whether for different chaotic systems the Feigenbaum number and Lyapunov exponent are universal. This involves producing computational programs capable of plotting bifurcation diagrams, Lyapunov exponent plots and careful analysis of the bifurcation diagram to calculate the Feigenbaum number for each map. Using these results comparisons between the different systems can be made to determine the mutual or different properties.

Methods

Wolfram Mathematica was used to create computational programs capable of producing the BF diagrams and LE plots displayed.

A bifurcation diagram provides a visual representation of how a dynamical system evolves through small changes of a parameter, these bifurcations are important scientifically as they provide representation of instabilities¹. A mathematical physicist Mitchell Feigenbaum explored the route to chaos of the logistic map and found a relationship between the period-doublings which occur via the bifurcations. The relationship was a ratio of the consecutive values of control parameter ' μ ' where the bifurcation splitting occurs². The equation for calculating the FB number is,

$$d = \lim_{n \rightarrow \infty} \frac{\mu_n - \mu_{n-1}}{\mu_{n+1} - \mu_n}$$

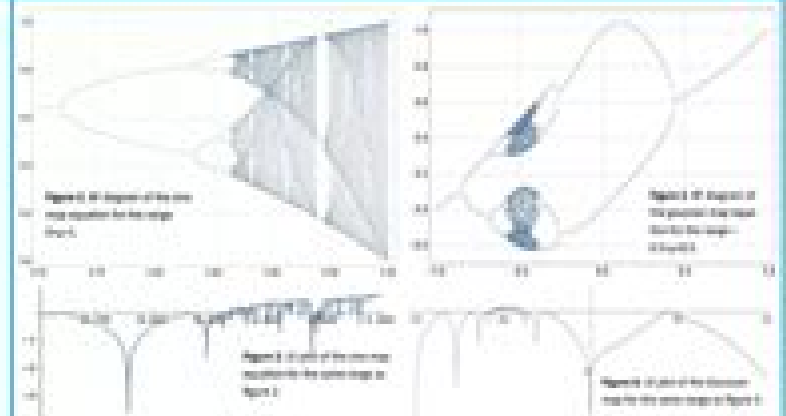
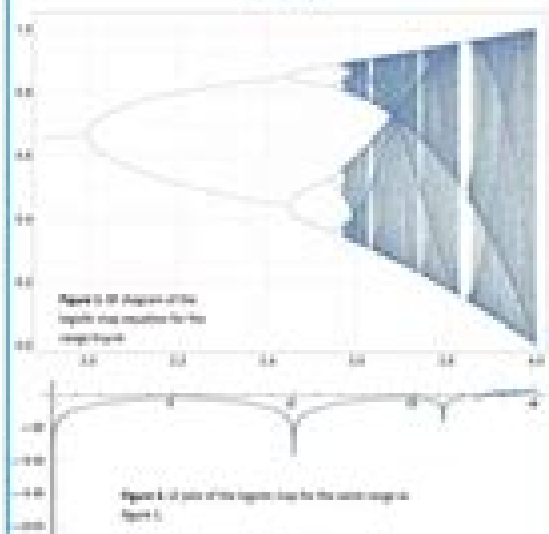
Where ' n ' is the order of the splittings and each μ_n corresponding to its order. A Lyapunov stable point is where that all trajectories near that fixed point remain close to it for all time.

The Lyapunov exponent is a measurement of the sensitive dependence on the initial conditions of the system and a plot of the Lyapunov exponent for changes in the control parameter gives a measure of whether this system is chaotic (positive exponent) or non-chaotic (negative exponent)³. The LE is defined as,

$$\lim_{n \rightarrow \infty} \left[\frac{1}{n} \sum_{i=0}^{n-1} \ln |f'(x_i)| \right]$$

where ' n ' is the number of iterations, $f'(x)$ is the first differential of the maps equation applied to the value of ' x ' at that point in the list. A chaotic system is one which seems completely random but in fact is deterministic, highly sensitive to initial conditions and one small error in a measurement of the initial condition produces an error which grows exponentially making the system un-deterministic or unpredictable. This effect is also called the butterfly effect and can be seen in many dynamical systems such as the weather, climate, pendulum, populations and more⁴.

Results



The sine map and the logistic map look extremely similar for the range $0 < \mu < 1$ and $0 < \mu < 1$ respectively, both are smooth, concave down and have a single maximum (unimodal). Both maps have the same vertical scale but differing horizontal scales, the difference in the horizontal scale is a factor of 4 due to the maximum of the quadratic line for the sine plot being μ and μ^2 for the logistic map. The periodic windows occur in the same order and with the same relative sizes. The biggest difference between the two maps in these regimes is the period doublings occur later in the logistic map and are thinner⁵. The Gauss map is significantly different to the other two maps in both BF diagram and LE plot, the biggest characteristic of this map is that it reaches a maximum chaotic behaviour and reverses back to periodic behaviour. Only a small area of the Gaussian LE plot is above zero (chaotic).

Conclusion

Maps of the form $x_{n+1} = \mu f(x_n)$ where $f(0) = f(1) = 0$ display the same structure on a bifurcation diagram. As μ is varied, the order in which stable period solutions appear is independent of the unimodal map iterated⁶. The LE is very much dependent on the system at hand, it measures where the system is stable or unstable so for example a damped oscillator will be stable at different points to the climate of the Earth. The LE is also very much dependent on initial conditions, this displays the nature of the un-deterministic nature of chaos. Feigenbaum came up with a theory on why the constant he discovered occurs and it is based on a theory called Renormalization. The renormalization theory is based on the self-similarity of larger the 'fractal' structure of the maps where the smaller branches look like the earlier branches except they are scaled down in both the x and μ directions. This theory explains how the FB number is universal for unimodal maps with a single maximum. This theory could be applied to other shaped maps.

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