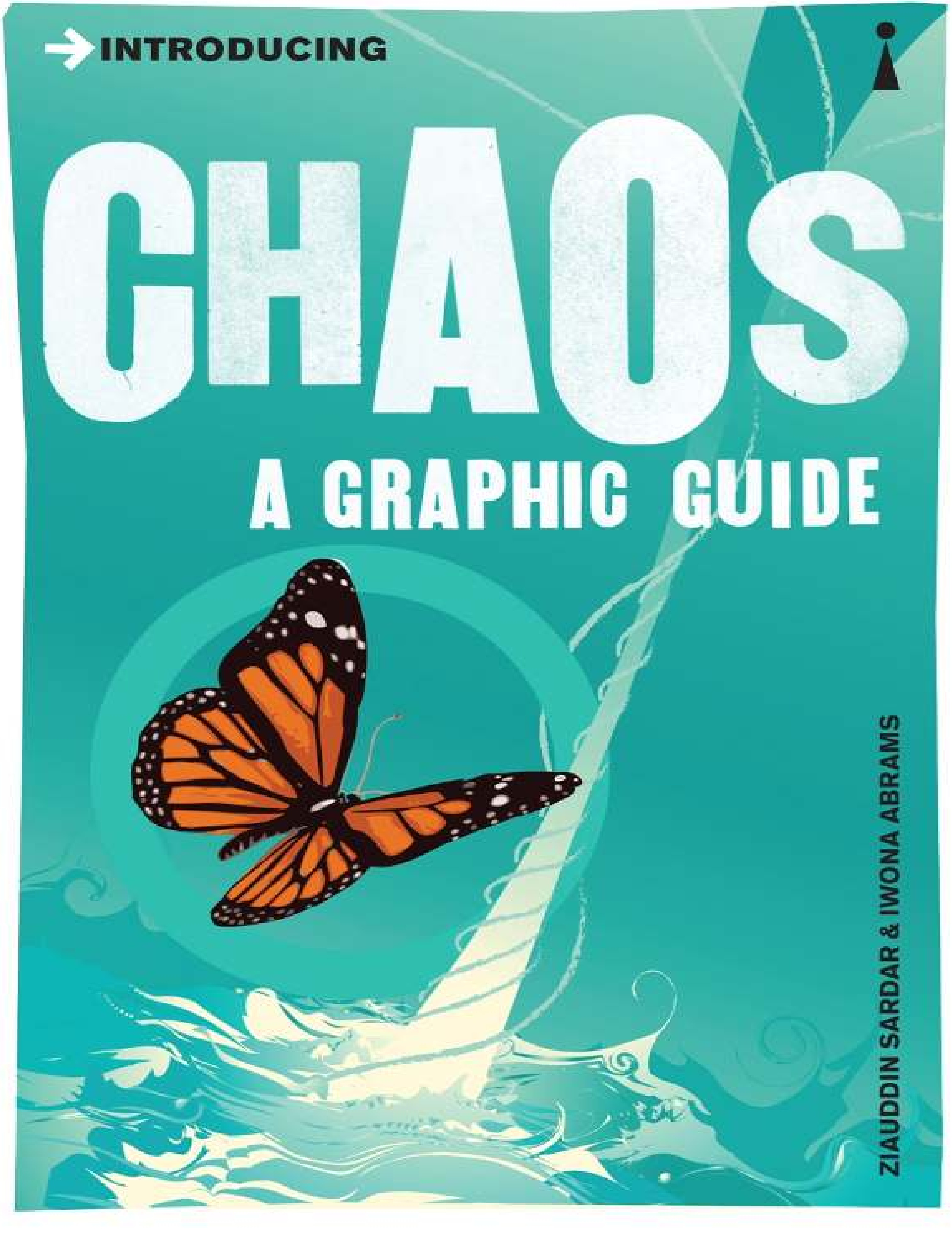
INTRODUCING
CHAOS
A GRAPHIC GUIDE
ZIAUDDIN SARDAR & IWONA ABRAMS

INTRODUCING
CHAOS

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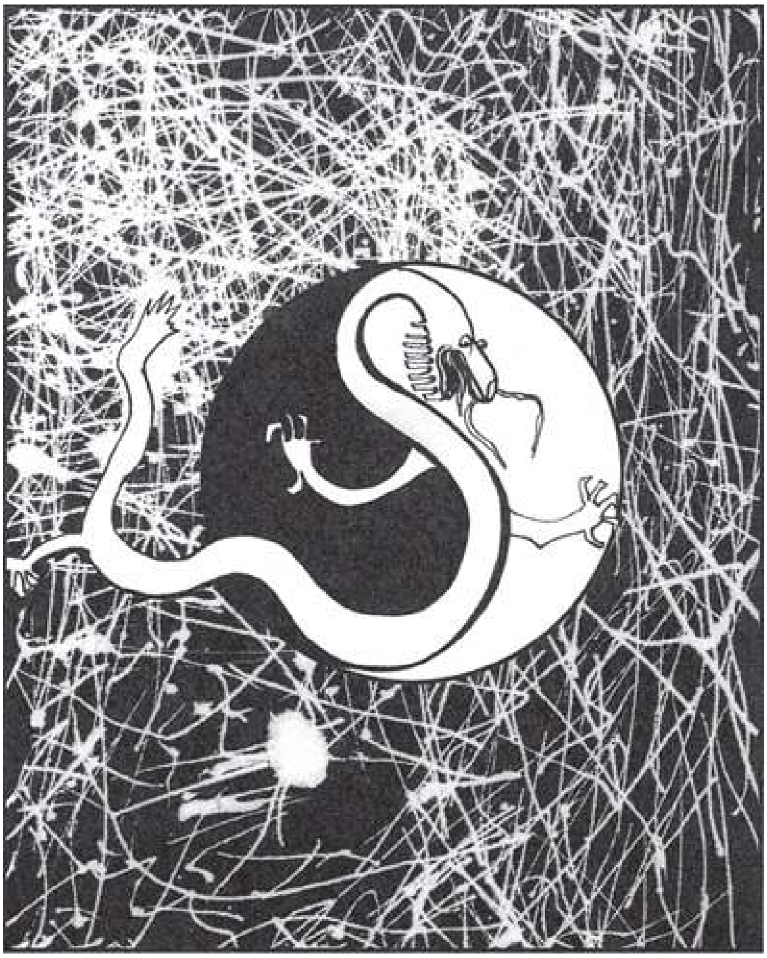
Contents

Yin, Yang and Chaos

Ancient Chinese thought recognized that chaos and order are related. In Chinese myth, the dragon represents the principle of order, yang, which emerges from chaos. In some Chinese creation stories, ray of pure light, yin, emerges out of chaos and builds the sky. Yin and yang, the female and male principles, act to create the universe. But even after they have emerged from chaos, yin and yang stil retain the qualities of chaos. Too much of either brings back chaos.



Ancient Chaos

Hesiod, a Greek of the 8th century B.C., wrote the **Theogony**, a cosmological poem which states that "first of all Chaos came to be", and then the Earth and everything stable. The ancient Greeks seem to have accepted that chaos precedes order, in other words, that order comes from disorder.

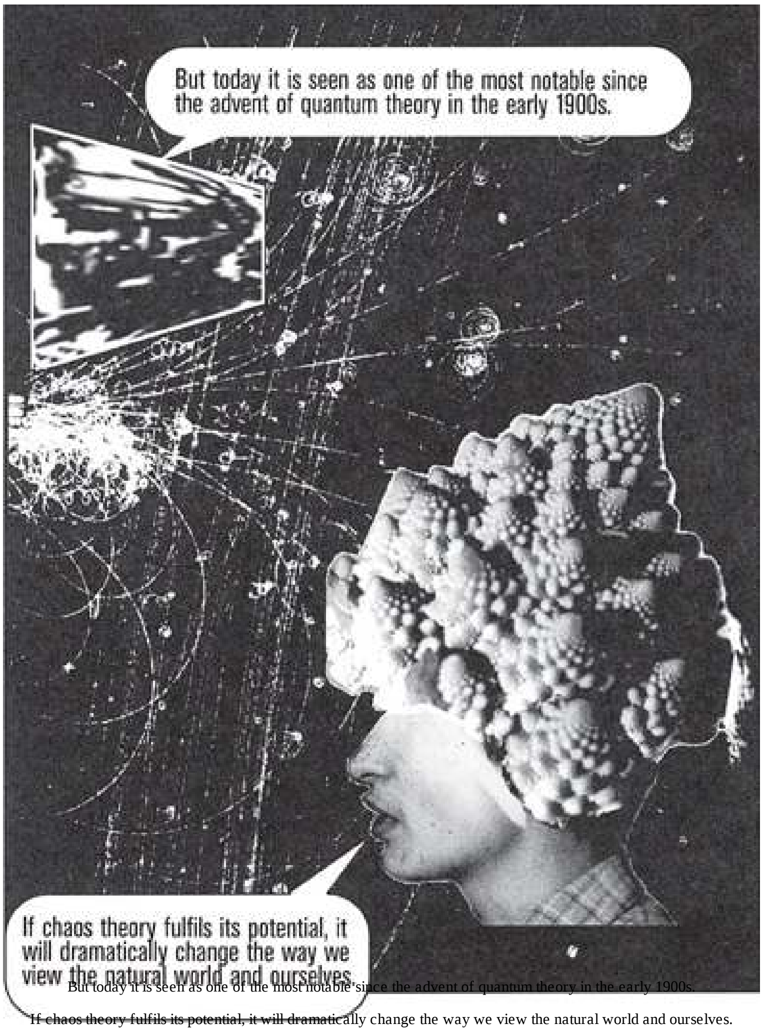
Nothing further was made of this 'mythical' idea ...

Until recently in the 20th century when chaos theory arrived.

Chaos Theory

Chaos theory is a new and exciting field of scientific inquiry.

The phenomenon of chaos is an astounding and controversial discovery that most respectable scientists would have dismissed as fantasy just a decade or so ago.



But today it is seen as one of the most notable since the advent of quantum theory in the early 1900s.

If chaos theory fulfils its potential, it will dramatically change the way we view the natural world and ourselves.

Why is Chaos Exciting?

Chaos is exciting for all these reasons ...

It connects our everyday experiences to the laws of nature by revealing the subtle relationships between *simplicity* and *complexity* and between *orderliness* and *randomness*.

It presents a universe that is at once deterministic and obeys the fundamental physical laws, but is capable of disorder, complexity and unpredictability.

It shows that predictability is a rare phenomenon operating only within the constraints that science h
filtered out from the rich diversity of our complex world.

It opens up the possibility of simplifying complicated phenomena.

It combines imaginative mathematics with the awesome processing power of modern computers.

It casts doubt on the traditional model-building procedures of science.

It shows that there are inherent limits to our understanding and predicting the future at all levels of complexity.

It is strikingly beautiful! Shakespeare had it right when he had Hamlet say in Act 1, scene 5 ...

There are more things in heaven and earth Horatio, Than are dreamt of in your philosophy.

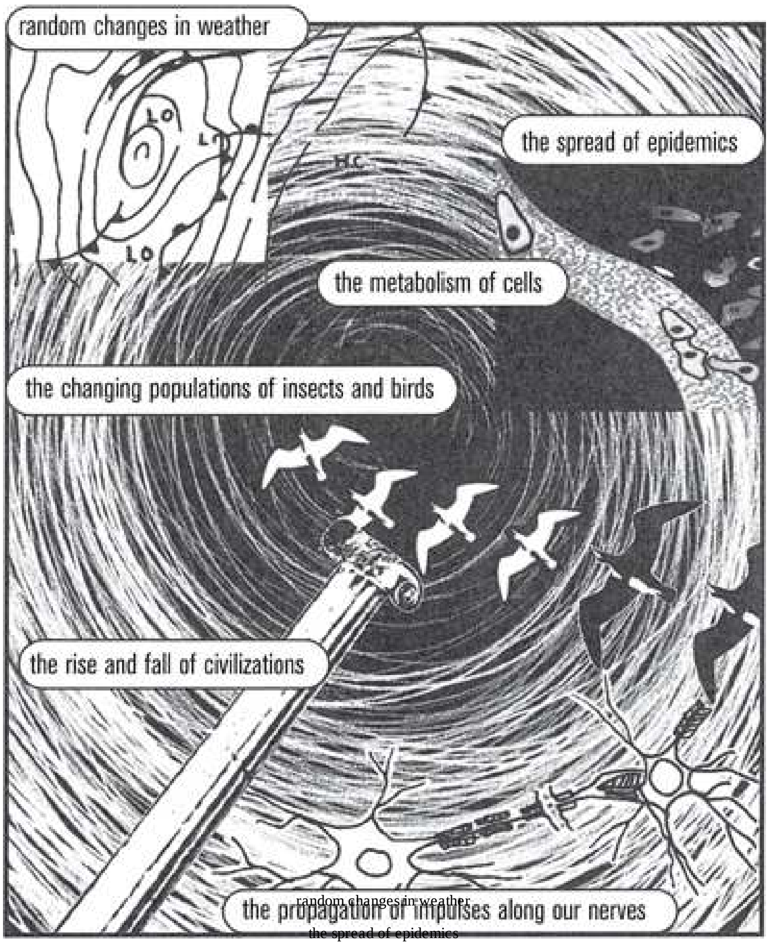
Hi! I'm Cordiallia Cauliflower. Just look at what chaos has done to me!

Where Does Chaos Come From?

Three major recent developments have made chaos a household word.

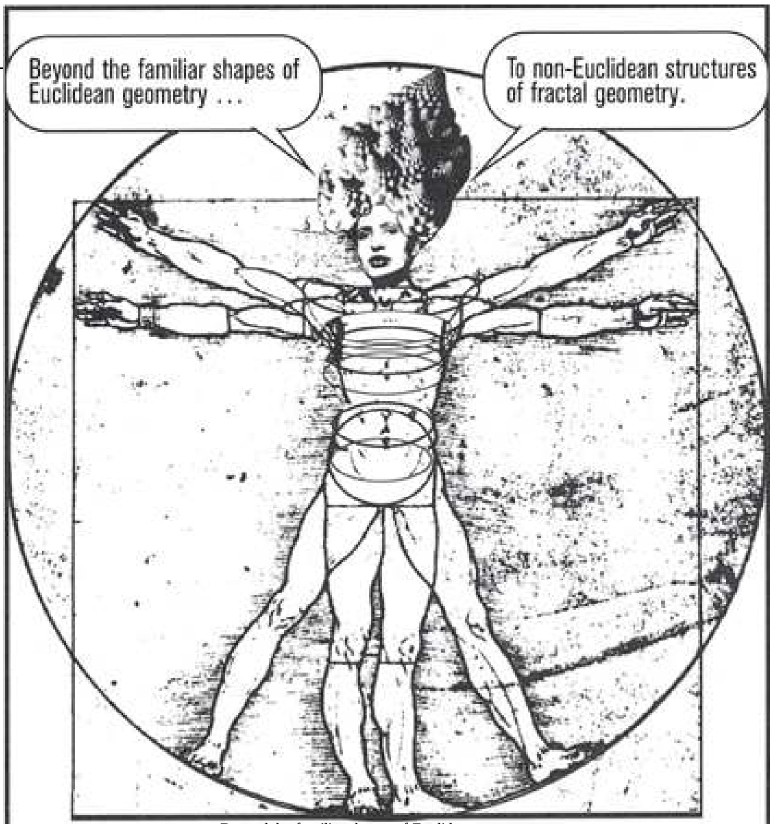
1. Breathtaking computing power that enables researchers to perform hundreds of millions of complicated calculations in matters of seconds.

2. The rise in computing power has been accompanied by a growing scientific interest in irregular phenomena such as ...



random changes in weather
the spread of epidemics
the metabolism of cells
the changing populations if insects and birds
the rise and fall of civilizations
the propagation of impulses along our nerves

3. Chaos theory was born when these developments were combined with the emergence of a new styl of geometrical mathematics ...



Beyond the familiar shapes of Euclidean geometry ...

To non-Euclidean structures of fractal geometry.

These developments have made an impact in almost every field of human endeavour. Chaos theory has been like a sea into which flow the rivers and tributaries of almost every discipline and subject – from mathematics, physics, astronomy, meteorology, biology, chemistry, medicine to economics and engineering, from the study of fluids and electrical circuits to the study of stock markets and civilizations.

Defining Chaos

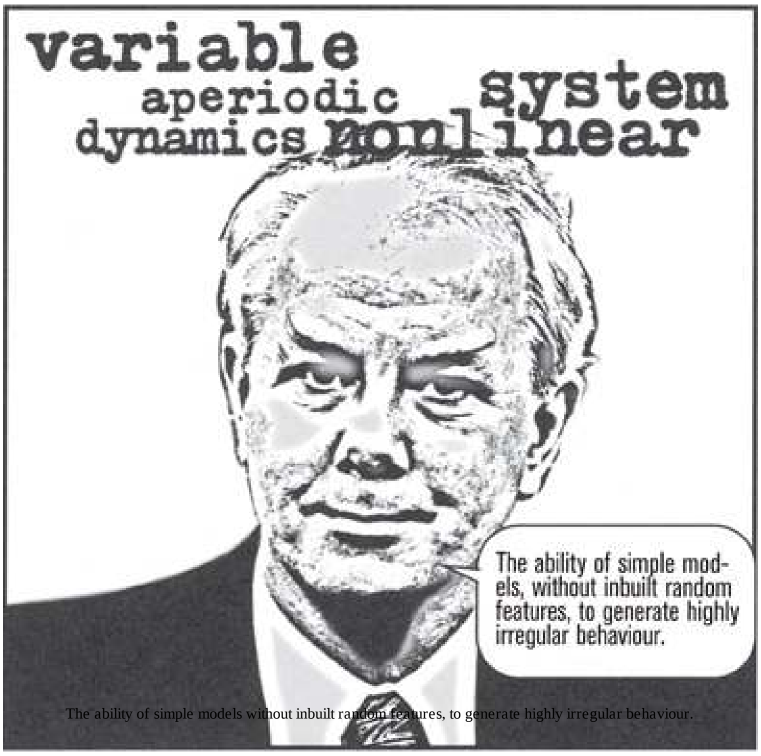
Chaos has been variously defined. Here are just a few examples ...

“A kind of order without periodicity.”

“Apparently random recurrent behaviour in a simple deterministic (clock-work-like) system.”

“The qualitative study of unstable aperiodic behaviour in deterministic nonlinear dynamical systems

And here’s another by a mathematician in the field, **Ian Stewart.**



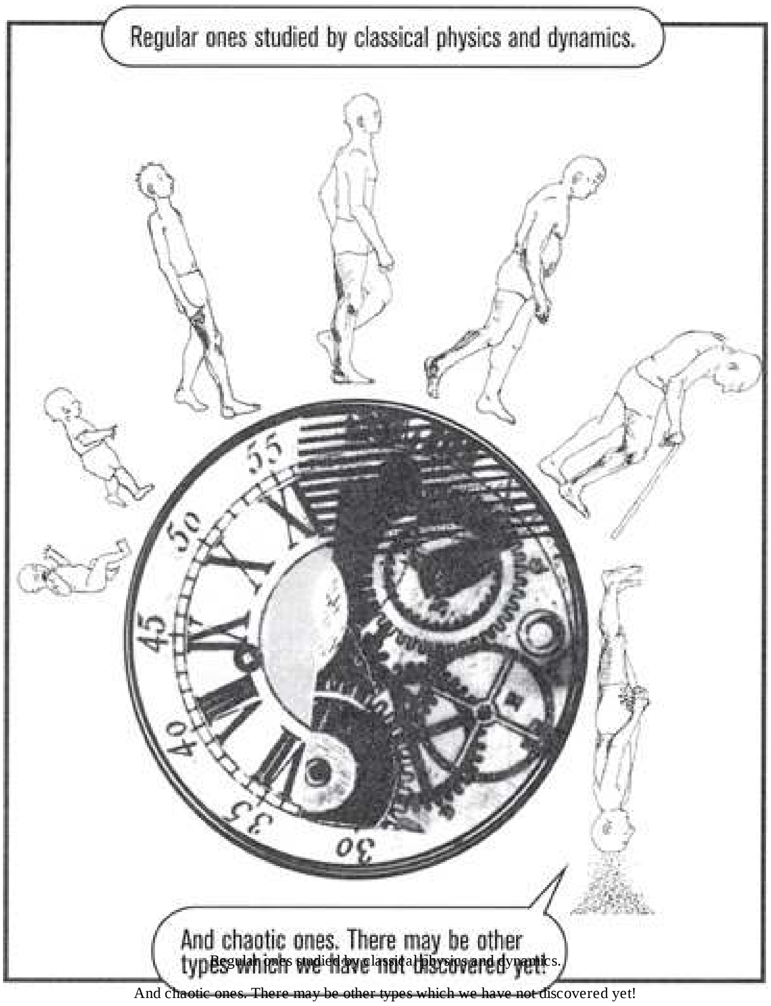
The ability of simple models without inbuilt random features, to generate highly irregular behaviour.

Technical definitions of chaos are not easy to understand. So let’s begin to familiarize ourselves with its terminology.

The Language of Chaos

Dynamic, Change and Variable

Chaos is a *dynamic* phenomenon. It occurs when something *changes*. Basically, there are two types o changes.

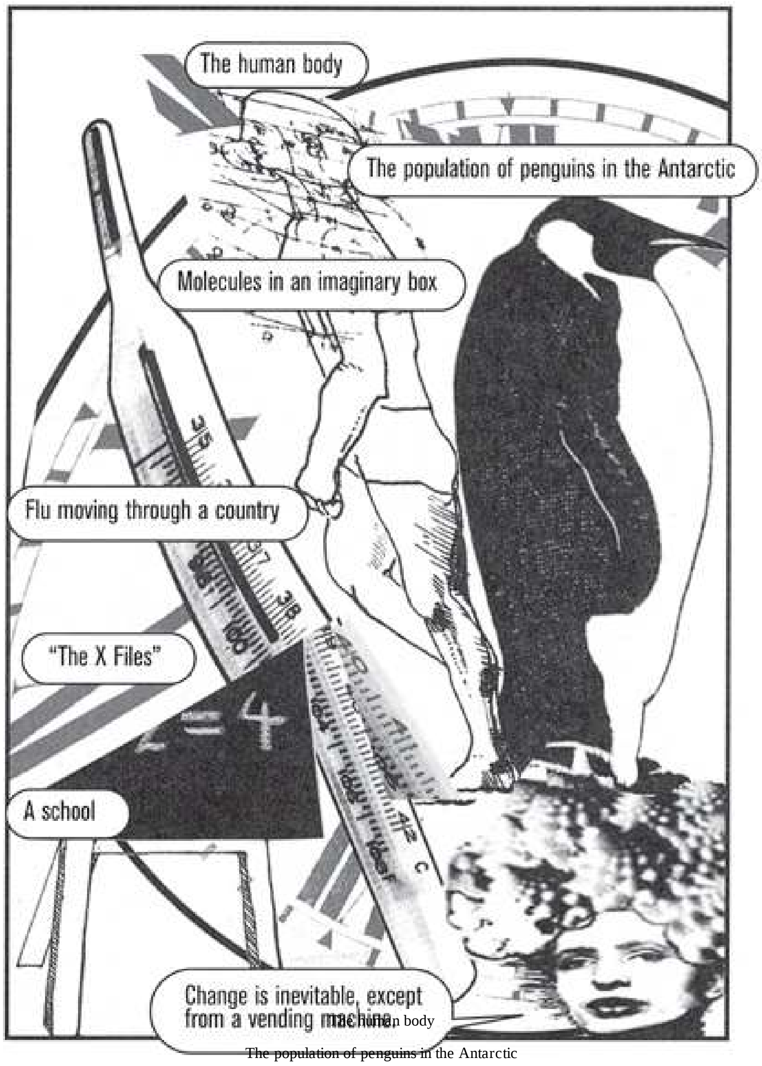


Regular ones studied by classical physics and dynamics.
And chaotic ones. There may be other types which we have not discovered yet!

What is changeable in a given situation is referred to as a **variable.**

Systems

Any entity that changes with time is called a **system.** Systems thus have variables. Here are some examples of systems.



The human body

The population of penguins in the Antarctic

Molecules in an imaginary box

Flu moving through a country

'The X Flies'

A school

Change is inevitable, except from a vending machine.

Defining Systems

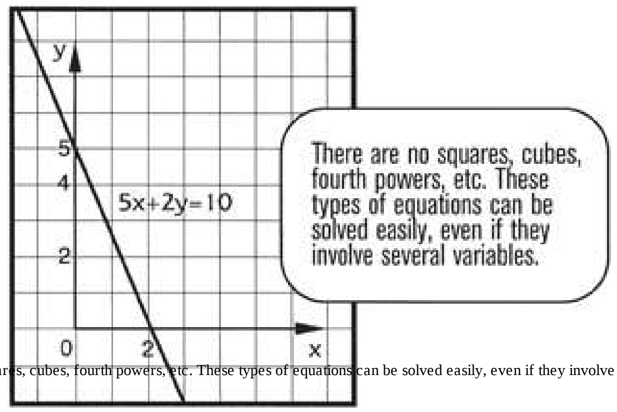
A **deterministic system** is one that is predictable, stable and completely knowable. The classic example of a deterministic system is an old-fashioned grandfather clock. The balls on a snooker tabl behave within the boundaries of a deterministic system.

In classical physics, the universe itself was considered to be a deterministic system.

Give me the past and present co-ordinates of any system and I will tell you its future.

In **linear systems**, variables are simply and directly related. Mathematically, a linear relationship ca be expressed as a simple equation where the variables involved appear only to the power of one:

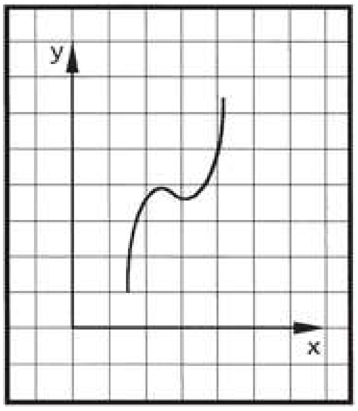
X = 2y + Z



There are no squares, cubes, fourth powers, etc. These types of equations can be solved easily, even if they involve several variables.

Nonlinear relationships involve powers other than one. Here is a nonlinear equation:

$$\mathbf{A = 3B^2 + 4C^3}$$

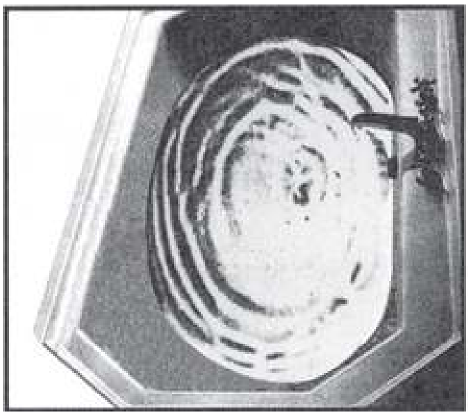


Such equations are much harder to analyze and frequently need the help of a computer to understand.

Periodic and Aperiodic Equations

A **period** is an interval of time characterized by the occurrence of a certain condition or event. A variable in a **periodic system** exactly repeats its past behaviour after the passage of a fixed interval o time – think of a swinging pendulum.

Aperiodic behaviour occurs when no variable affecting the state of the system undergoes a complete regular repetition of values – visualize the flow of water as it goes down a sink.

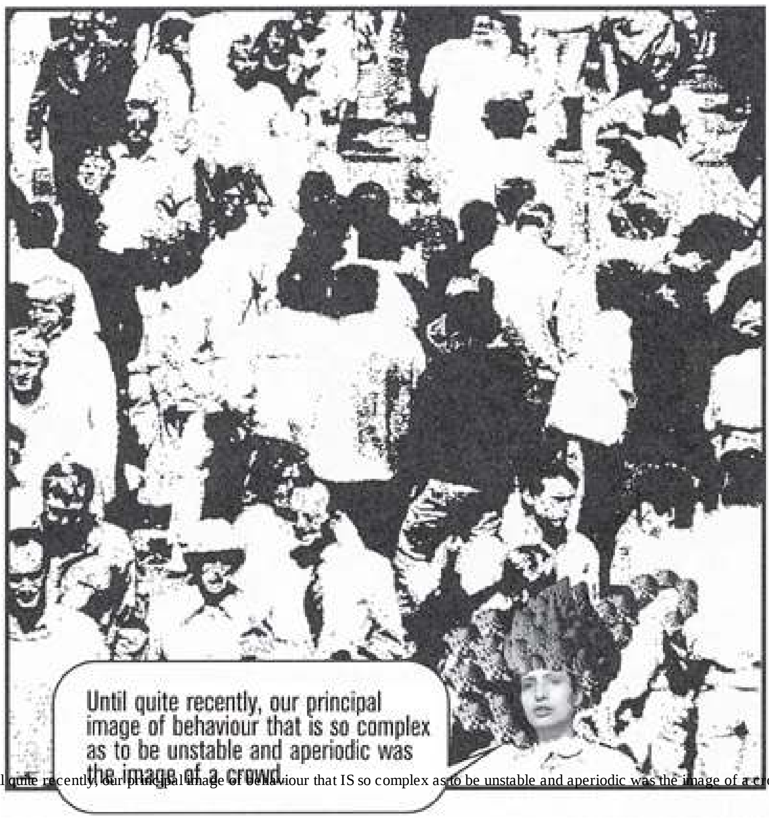


Unstable aperiodic behaviour is highly complex. It never repeats itself and continues to show the effects of any small perturbation to the system. This makes exact predictions impossible and produce a series of measurements that appear random.

That's why, in spite of our satellite observations and computer models, it is still impossible to predict the weather accurately.

What is Unstable Aperiodic Behaviour?

Behaviour that is unstable yet periodic is difficult to imagine – indeed, it appears to be a contradictio in terms. However, human history provides us with several examples of just such a phenomenon. It i possible to chart broad patterns in the rise and fall of civilizations. We can see that these patterns are *periodic*. But we know that events never actually repeat themselves exactly. In this realistic sense, history is *aperiodic*. We can also read in history textbooks that seemingly small unimportant events have led to long-lasting changes in the course of human affairs.



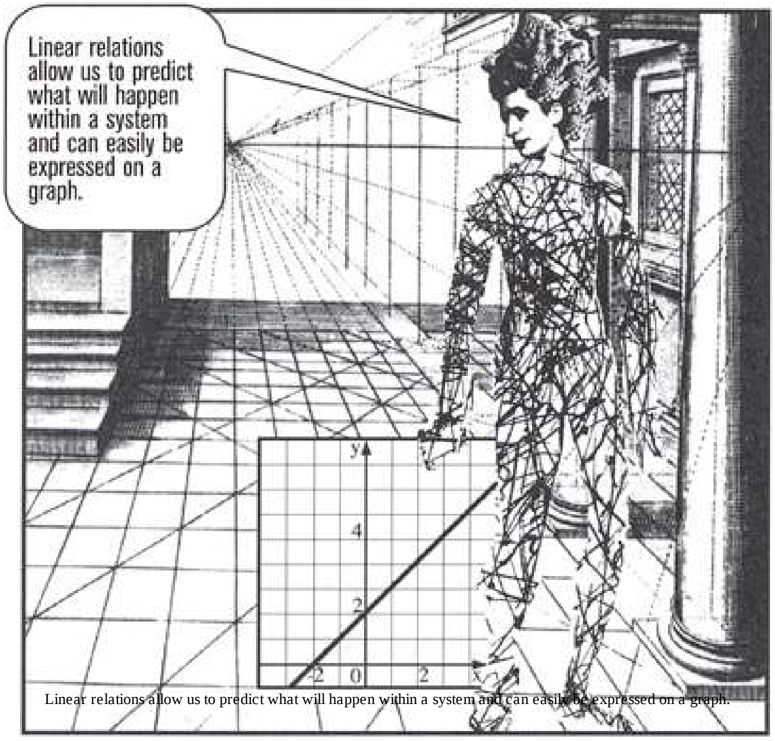
Until quite recently, our principal image of behaviour that IS so complex as to be unstable and aperiodic was the image of a crowd.

Now that our perception has changed, we see such behaviour in even the commonest events: water dripping from a tap, a flag waving in the breeze, the fluctuation of animal populations.

Linear Systems

So: simply put, chaos is the occurrence of aperiodic, apparently random events in a deterministic system. In chaos there is order, and in order there lies chaos. The two are more closely connected tha we ever thought before.

But since deterministic systems are predictable and stable, this seems to be illogical. As a matter of habit, humans have looked for patterns and linear relations in what they see.



Linear relations allow us to predict what will happen within a system and can easily be expressed on a graph.

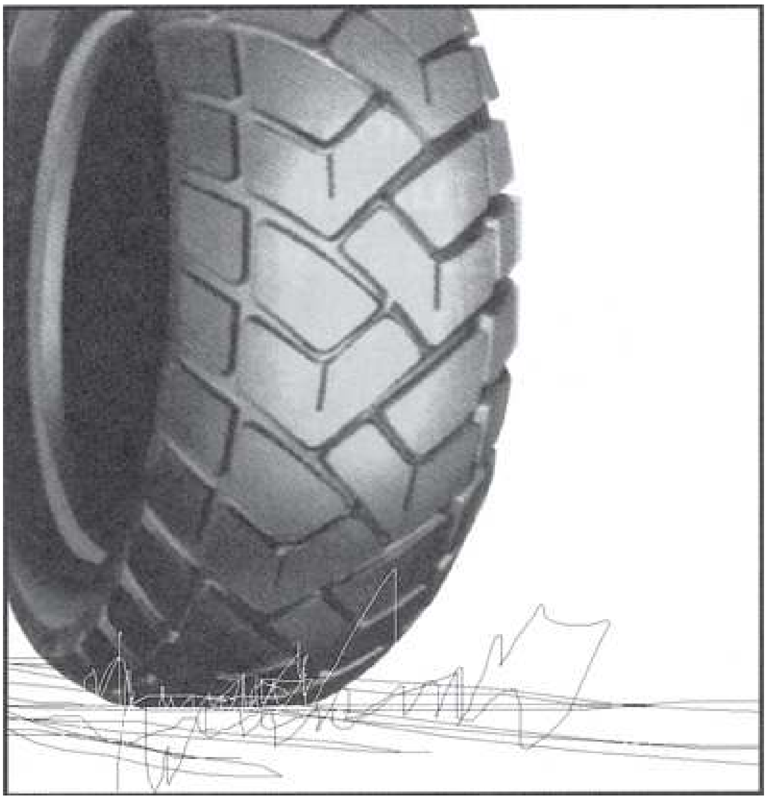
In other words, they form a straight line on the graph and we know where that line is going.

Linear relationships and equations are solvable. That makes them easy to think about and work with.

Nonlinear Complication

Nonlinear equations, on the other hand, cannot be solved. Friction, for example, often makes things difficult by introducing nonlinearity. Without friction, the amount of energy required to accelerate an object is expressed in a linear equation ...

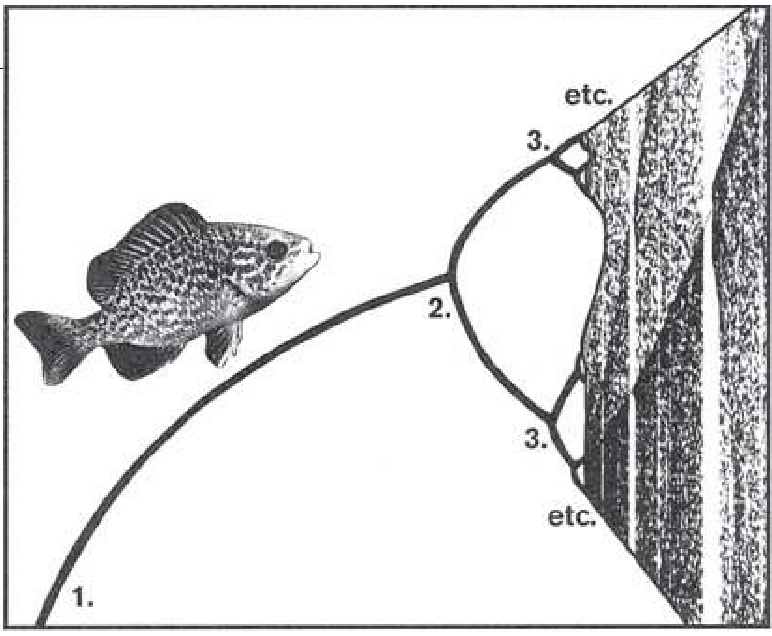
force = mass x acceleration



Friction complicates things because the amount of energy changes, depending on how fast the object is moving.

Nonlinearity, therefore, changes the deterministic rules within a system and makes it difficult to predict what is going to happen.

There is a famous example of a nonlinear relationship in the history of chaos. **Robert May**, a biologist, was studying an imaginary population of fish. The mathematical model he used for the fish population was the equation $x_{next} = rx(1-x)$, where **x** represents the present population of fish in an area. When the parameter, **r** (rate of growth) was 2.7, he found the population to be .6292.



1. As the parameter rose, the final population rose slightly too, making a line that rose as it moved from left to right on the graph.

2. Suddenly, as the parameter passed 3, the line broke in two and May had to plot for two populations. This split meant that the population was going from a one-year cycle to a two-year cycle.

3. As the parameter rose further, the number of points doubled again and again. The behaviour was complex yet regular. Beyond a certain point, the graph became totally chaotic – and the graph was completely blacked in. Yet even in the midst of the chaos, stable cycles returned as the parameter was increased.

Most forces in real life are nonlinear. So why have we not discovered this before? The reason that chaotic behaviour has not been studied until now is because scientists reduced difficult nonlinear problems to simpler linear ones in order to analyze them. **Galileo's** work with gravity provides us with a good example. Galileo (1564–1642), an Italian physicist, disregarded small nonlinearities in order to get neat results.

Feathers do not fall with the same speed as a ball, due to air resistance. H'm, so what ...

An ideal scientific world was created where regularities were isolated from actual experience and "disorder".

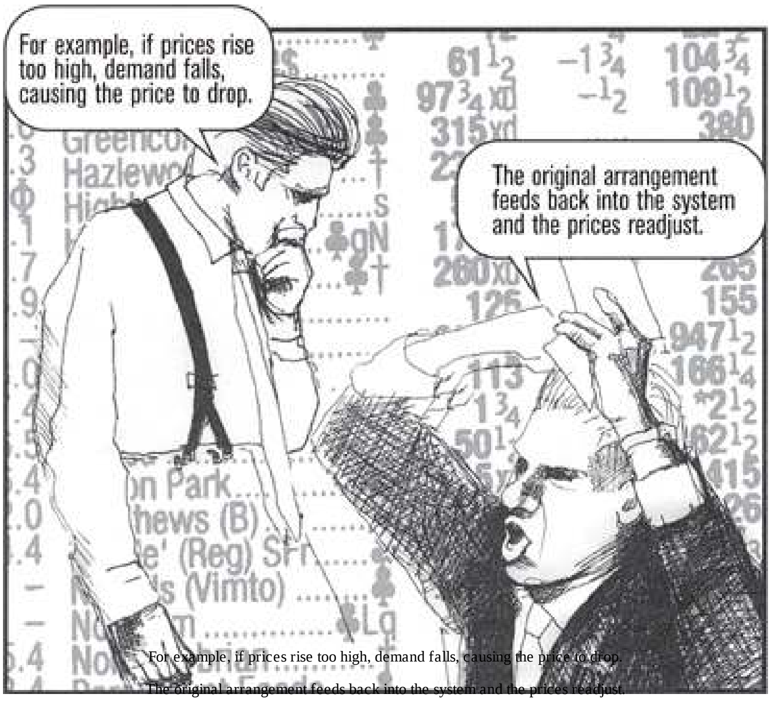
Since the advent of "modern" Western science, we have been living in a world which acts as if the platypus was the only animal in existence!

Feedback

Feedback, like nonlinearity, is also common in real-life events. Feedback is a characteristic of any system in which the output, or result, affects the input of the system, thus altering its operation.

Feedback is most commonly observed when a microphone is in use. Some of the output signal is literally “fed back” into the system and causes the screeching sounds that engineers and musicians dread. Feedback can, however, be useful in the production of amplifiers where it is deliberately loope back into a system.

Feedback is also observed on the trading floor and is actually a form of self-regulation.



For example, if prices rise too high, demand falls, causing the price to drop.
The original arrangement feeds back into the system and the prices readjust.

We can also see feedback loops when an enzyme produces a copy of itself in a chemical reaction. Th is a positive feedback loop. This happens when DNA becomes a living organism and is very commor in organic chemistry.

However, scientists have tended to ignore feedback to create simple models that are easier to study and work with. They knew about feedback and complexities but did not understand them. For example, it is much easier to study population as a simple linear system than one involving feedback and complexity.