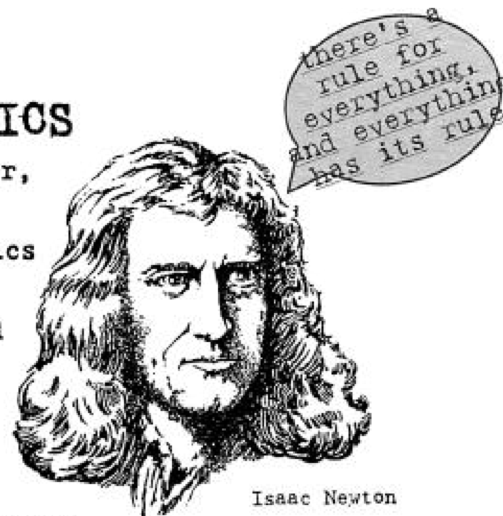
INTRODUCTION

THE OLD PHYSICS

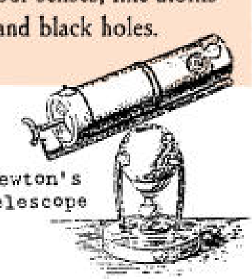


Isaac Newton

★ Modern physics - or, at least, the first phase of modern physics - began with Isaac Newton, **in the second half of the 17th century. The most important thing Newton did was to spell out that the entire Universe is governed by simple rules, which also apply to things going on here on Earth. The most famous example of this is his** LAW OF GRAVITATION, **which explains both the way an apple falls to the ground from a tree and how the Moon stays in orbit around the Earth - and much more besides.**

OLD AND NEW PHYSICS

Old physics is the stuff we learn in school, the kind of laws that apply to objects we can see and touch, like billiard balls or cars. New physics deals with things that are inaccessible to our senses, like atoms and black holes.


Newton's telescope

NEWTON AND GRAVITY

★ *This law of nature is what is known as an* INVERSE-SQUARE LAW *– the force of attraction between two objects depends on their two masses multiplied together, divided by the square of the distance between them.* So if the same two objects are twice as far apart the force is reduced to a quarter, while if they're three times as far apart it is reduced to a ninth. And so on.

★ But, for the moment, the law itself is less important than the fact that there is a unique law that describes the force of GRAVITATIONAL ATTRACTION operating between any two objects in the Universe –

between a pencil on my desk and the cat in the next room, between the Moon and the Earth, or between two galaxies on opposite sides of the Universe, or even between my cat and a distant galaxy.

BEFORE NEWTON

★ Before Newton came along, even scientifically minded people commonly believed the Universe was governed by rules devised by the gods, or God. When, in 1609, **Johannes Kepler** realized that something made the planets stay in orbit around the Sun, he called it the 'Holy Spirit Force', and nobody laughed at him for doing so. ***The Universe was seemingly at the mercy of mysterious and incomprehensible forces, which might change from day to day or from place to place.***

KEY WORDS

GRAVITY: the force of attraction between two masses

GRAVITATION: the influence any object exerts on other objects in the Universe simply by having mass

Johannes Kepler (1571–1630)

German astronomer who discovered the laws of planetary motion, which helped Newton develop his theory of gravity. Kepler used observations of the planets compiled by **Tycho Brahe** (1546–1601). Before joining Brahe in Prague, he trained for a career in the Church, then worked as a teacher of mathematics at a Protestant seminary in Graz.

Isaac Newton (1642–1727)

Newton was active in many fields. He studied alchemy (still almost respectable at that time) and theology, and served as a Member of Parliament (his knighthood was for political work, not science) and as Master of the Royal Mint and President of the Royal Society. Newton was very secretive about his work, and often got involved in huge rows with other scientists about who had thought of an idea first (usually he had thought of it, but hadn't bothered to tell anyone!). His great work in physics was completed before he was 30, but only published in 1687, at the urging of Edmond Halley. In the 1690s Newton suffered a mental breakdown, and although he recovered sufficiently to lead a normal life, he did no more scientific work.

Edmond Halley

A CLOCKWORK UNIVERSE

* After Newton, the Universe was perceived in a quite different way - as a kind of cosmic clockwork mechanism, running predictably in accordance with laws of physics that could be determined from experiments here on Earth. The laws might be God-given (Newton thought they were), but they were now seen as being the same everywhere and at all times.

Newton identified the laws of the Universe

Newton suffered a breakdown from overwork

FUNDAMENTAL LAWS

★ *The predictability of the Newtonian Universe was based on three other fundamental laws discovered by Newton.* Known as Newton's LAWS OF MECHANICS (or laws of motion), they are spelled out in his great book *Philosophiae Naturalis Principia Mathematica (The Mathematical Principles of Natural Philosophy)*, usually referred to simply as the Principia.

★ *These three laws formed the basis of physics for the next 200 years – and still suffice to explain the way things behave in the everyday world, even though some of the things explained by them (such as the flight of a jet aircraft, or the journey of a space probe to the planet Jupiter) were undreamed of by Newton himself.*

Newton's first law of mechanics

The first of Newton's three laws of mechanics immediately shows how physicists often have to discount 'common sense' in order to get a grip on the way the world works. ***It insists that any object – by implication, any object in the entire Universe – either stays still or keeps moving in a straight line unless some force is applied to the object.*** The standing still part is no problem, so far as common sense is concerned. Here on the surface of the Earth most things do stay still, unless they are given a push. But if given a push, they certainly don't keep moving in a straight line for ever. They slow down and come to a halt.

KEY WORDS

MECHANICS: the branch of physics that deals with the way things move and the forces that make them do so

ON AND ON AND ON...

this could go on forever

★ The first step in Newton's insight was to realize that things only come to a halt because they are being influenced by an outside force - the force of friction. Things stop moving because they are rubbing against other things, even if the other things are only molecules of air brushing past.

Galileo realized the balls would keep on rolling unless something stopped them

UNSTOPPABLE

Imagine something sitting in empty space then given a quick push (a fairly obvious thing to imagine today, in the age of space flight, but a huge leap of the imagination in the 17th century). It will keep moving in a straight line for ever unless some other force acts on it.

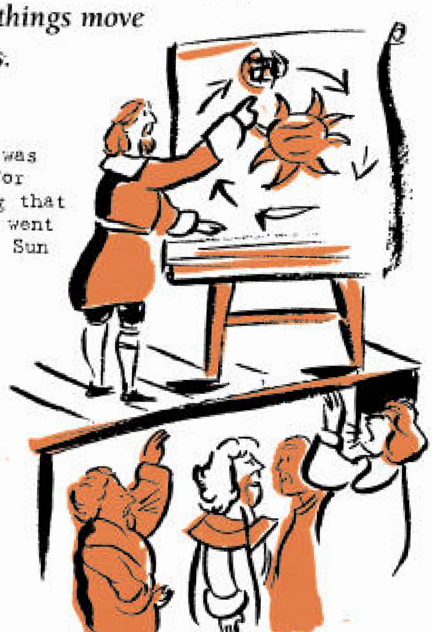
...FOR EVER

★ This business about friction bringing things to a halt was, in fact, already partly understood before Newton came onto the scene. In particular, **Galileo Galilei** had realized that things would keep moving for ever if no external force acted on them. He came to this conclusion after carrying out a series of experiments in which balls were rolled down inclined planes. ***The balls rolled off towards the horizon, and Galileo realized that without friction they would keep rolling for ever.***

who knows where this ball will end up

...OR ROUND AND ROUND

★ ***At this point Galileo made a daring but erroneous extrapolation.*** Like all educated people of his day, he knew that the Earth is round. So an object that keeps moving towards the horizon for ever must be following a circular path around the surface of the Earth, and will eventually end up back where it started from. A least it would do if there were no mountains or other obstructions in its way. ***This led Galileo to believe there was a fundamental law of nature which said that, left to their own devices, things move in circles.***



Galileo was tried for proclaiming that the Earth went round the Sun

Galileo Galilei

Galileo Galilei (1564–1642)

Galileo was the first person to use a telescope to observe the stars and planets scientifically. He studied medicine at the University of Pisa, but dropped out to become a scientist. His astronomical observations made him famous, and he was one of the first scientists to publicly support the idea that the Earth goes round the Sun. As a result, when 69 years old and in frail health, he was tried for heresy, forced to recant under threat of torture, and confined to house arrest for the rest of his life. The publicity of his trial in Catholic Rome helped to ensure that his ideas were taken up in Protestant northern Europe.

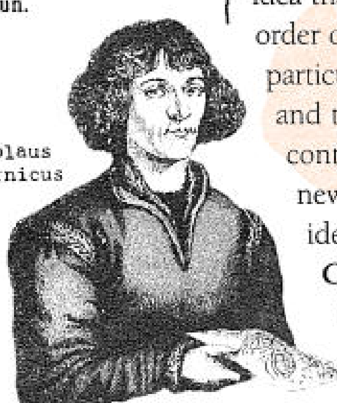
CIRCULAR THINKING

★ Don't believe everything you see on TV. Those spaceships that appear to be steering a straight course are actually in orbit around the Earth, moving along more or less circular paths. And the things moving 'in straight lines' inside the spaceships - that is, in straight lines relative to the walls of the spaceship - are also circling the Earth.

orbiting spaceships follow a circular path

Heretical thinking

Nicolaus Copernicus (1473–1543) was a Polish astronomer who was the first scientist to promote the idea that the Earth goes round the Sun.



Nicolaus Copernicus

NEW, EXCITING AND HERETICAL

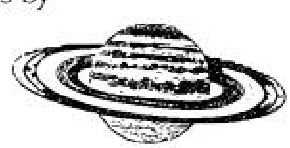
★ Galileo would have quite happily accepted those TV pictures as evidence in favour of his argument. Indeed, the idea that circular motion was the natural order of things would have seemed particularly convincing to Galileo and the better educated of his contemporaries because of a relatively new, exciting and (literally) heretical idea, proposed by **Nicolaus Copernicus**, that the planets – including the Earth – move in circles around the Sun.

ALL BECAUSE OF GRAVITY

★ ***When Newton said that the natural order of things in the Universe is for objects to move in straight lines, he had to explain why the planets stay in orbit around the Sun and don't fly off into space.*** This is where his law of gravity came into the picture, not only explaining how the Sun maintains a grip on its family of planets, but also why the orbits of the planets around the Sun are – as Johannes Kepler had discovered, in 1609, to the embarrassment of Galileo – actually elliptical, not circular.

★ ***It is all thanks to Newton's inverse-square law of gravity. Stated more fully, this law says that the force of*** ATTRACTION ***operating between two masses is equal to the two masses multiplied together, all divided by the square of the distance between them (hence 'inverse square') and then multiplied by a constant, known as the constant of gravity, which is the same everywhere in the Universe and at all times.***

★ The only way to find out the constant of gravity, which tells you the strength of the force of gravity, is by experiments – but once you know this constant everything else is easy to calculate.



Saturn

KEY WORDS

ATTRACTION:
any force that pulls two objects together

MASS:
the amount of matter there is in an object

GRAVITY SIMPLIFIED

The simplest way to picture the effect of gravity is to imagine a stone, tied to a string, being whirled round and round in a circle. The analogy isn't exact, because the stone is moving in a circle, not an ellipse. But the force acting along the string is just like the force of gravity: it pulls the stone inwards and keeps it 'in orbit'. Should the string break, the stone would fly off in a straight line, at a tangent to its 'orbit'.

NEWTON'S SECOND LAW

★ Newton's second law of mechanics also comes into the picture. The second law tells you how much the motion of an object is affected by a force applied to it. It says that a force applied to a mass causes an acceleration.

KEY WORDS

ACCELERATION: any change in the speed of an object or the direction in which it is moving, or both

VELOCITY: the speed of an object measured in a specific direction

FREE FALL: state of weightlessness felt (or not felt!) by any object moving under the influence of gravity only

ACCELERATION AND VELOCITY

★ ACCELERATION ***means a change in the*** VELOCITY ***of an object.*** And velocity – which is speed measured in a certain direction – has two properties. When the velocity changes, it may mean that the speed changes, as when you apply the brakes and bring a car to a halt in a straight line. Or it may mean that the direction of motion changes, as when you turn the wheel and take the car round a bend (or when a stone tied to a string whizzes round in a circle).

★ *So a change in velocity may involve a change in speed without any change in direction, or it may involve a change in direction without any change in speed, or it may involve a bit of both. They are all accelerations.*

if a cannonball is fired powerfully enough, it will travel right round the planet...

CURVING CANNONBALLS

I knew I was going round the bend

★ ***Newton himself made an analogy with a superpowerful cannon fired from the top of a tall mountain. Ignoring the effects of friction, imagine firing cannonballs off horizontally with increasingly powerful blasts from the cannon.***

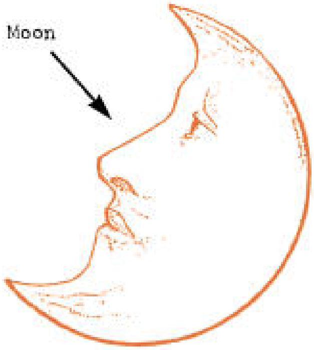
★ The first ball flies a little way towards the horizon and falls to the ground, tugged towards the centre of the Earth by gravity (it actually follows a curving, parabolic, path from the mouth of the cannon to the ground). The next ball travels a little further before gravity is able to pull it to the ground, and so on.

★ ***But remember that the Earth is not flat – it curves away under the flying cannonball, which is, of course, always being accelerated towards the centre of the Earth. Because the surface of the Earth is curved, the cannonballs fly further over it than they would if the Earth was flat.*** (Indeed, firing cannonballs off like this and measuring how far they travel would be a way of proving that the Earth is not flat!)

Good shot!

If the cannon is capable of producing a powerful enough blast, the flying cannonball will travel right round the planet and hit the rear of the cannon. It will have gone into orbit. ***Because it moves forward and falls sideways all the time, the sideways fall is exactly enough to keep it in orbit – in a state that is sometimes described as 'free fall'.***

...and hit the rear of the cannon



CANNONBALLS AND THE MOON

★ Like the cannonball, the Moon is always falling and always accelerating, even though its speed in its orbit does not vary significantly.

The tug of gravity

The orbit of the Moon around the Earth is a good example of acceleration at constant speed. The Moon would 'like' to keep moving in a straight line, but every time it moves forward, even a tiny bit, the force of the Earth's gravity tugs it sideways, deflecting it from a straight course. This constant sideways tugging keeps the Moon in its orbit.

KEY WORDS

ACTION:
(in Newton's laws) a force – something that 'acts' on something

REACTION:
the force that pushes back when an action acts on something

THAT APPLE AND THE MOON

★ Newton's second law says that when a force F is applied to a mass m it causes an acceleration that can be expressed as $a = F/m$. ***The bigger the force applied to the mass, or the smaller the mass subjected to the same force, the bigger the acceleration produced.***

★ This second law of motion combined with the inverse-square law of gravity explains both the acceleration produced in an apple falling from a tree at the surface of the Earth and the acceleration of the Moon falling sideways in its orbit around the Earth. ***In both cases, the cause is the same – the Earth's gravity.***

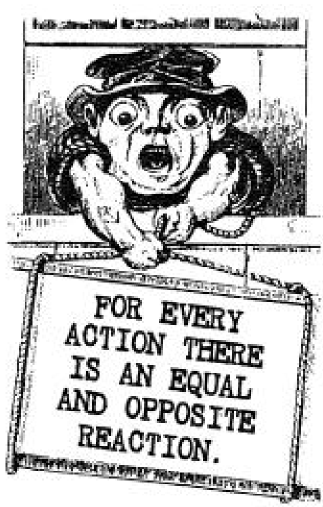
NEWTON'S THIRD LAW

★ Newton's third (and last) law of motion can also be understood by thinking about what happens when a cannon is fired. The cannonball goes out of the mouth of the cannon and off into the distance, while the cannon itself rolls

the Earth's gravity keeps the Moon in orbit

backwards in the opposite direction. Similarly, when you fire a rifle you feel a kick as the rifle recoils.

*** *Using the word 'action' where we would probably say 'force', Newton pointed out that for every* ACTION *there is an equal and opposite* REACTION.** A masterpiece of brevity, this law contains a large amount of information. First, it states that if you hit something, it hits back. This is quite easy to test. If you thump your fist on the table you can feel the reaction, quite unambiguously. The law also says that the action and the reaction are simultaneous.



Newton's third law of motion

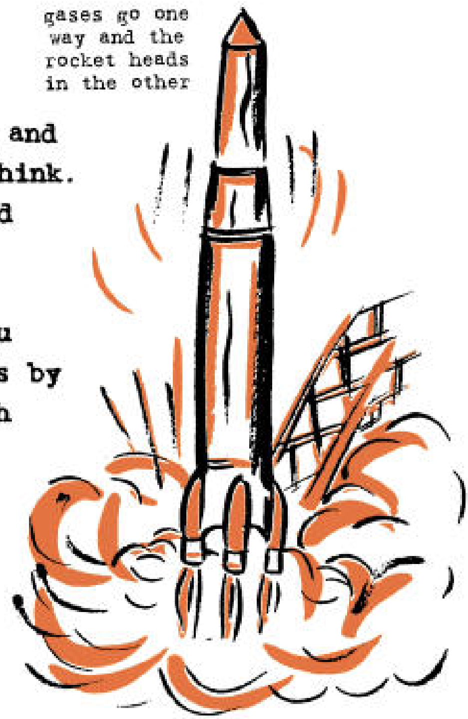
EQUAL, OPPOSITE AND INSTANTANEOUS

Newton's third law also points out that the reaction is equal and opposite to the initial force. In spite of this, the cannon only recoils a little bit, while the cannonball goes off into the distance – because the same force is being applied to a more massive object, and the acceleration produced is, remember, inversely proportional to the mass it is applied to. But the forces themselves (the action and reaction) always cancel out precisely.

ACTION AND REACTION

★ **There's more to action and reaction than you might think. The equality of action and reaction applies all the time: to yourself and everything around you. You are being pulled downwards by the Earth's gravity, which gives you your weight - but you are also pulling the Earth upwards by the same amount.**

gases go one way and the rocket heads in the other



How a rocket works

Newton's law of action and reaction also explains how a rocket works. The rocket motor fires exhaust gases out in one direction, and this produces a reaction which pushes the rocket in the other direction. There is no need for the exhaust gases to have anything to push against – which is why rockets work in the vacuum of space. ***All that matters is that hot gases are squirted one way, and the rocket heads the other.***

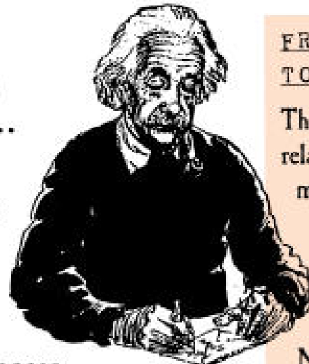
splutter broooom weeeee whoosh

THE EARTH MOVES?

★ If you were falling towards the ground from the top of a tall building, ***the Earth would also be moving up to meet you*** (but only by a tiny amount, since the acceleration depends inversely on the mass).

★ *When you stand still on the ground, your weight is a force pressing downwards on the ground – which responds by pushing upwards with an equal and opposite force, keeping you in place.*

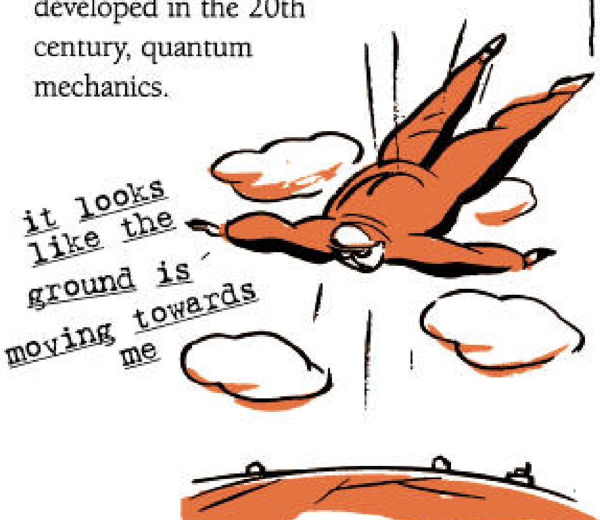
Albert Einstein



THE FUNDAMENTAL THINGS APPLY...

★ As the foregoing examples show, Newton's laws are still the fundamental principles on which physics operates for everyday purposes – on the scale of human beings, or even planets and stars.

★ But on a much larger scale – when we are talking about very massive objects, or the whole Universe – Newton's law of gravity is not quite good enough and we have to use the ideas developed by Albert Einstein in the 20th century, in his general theory of relativity. On a much smaller scale (smaller than atoms), Newton's laws of mechanics are not quite good enough either and we have to use another theory developed in the 20th century, quantum mechanics.



FROM STARS TO ATOMS

These two great ideas, relativity and quantum mechanics, form the basis of the new physics. But it is a sign of just how powerful Newtonian physics is that it applies very accurately to the behaviour of everything from stars to atoms, even though hardly anything was known about atoms when Newton was alive. ***Indeed, one of the greatest achievements of Newtonian mechanics is the way in which it has been used to explain the behaviour of gases, liquids and solids in terms of atoms and molecules, which move about and collide with one another in perfect obedience to Newton's laws.*** This second flowering of Newtonian theory happened in the second half of the 19th century – two centuries after he wrote the *Principia*.

bottom hardly moves, and the top hardly moves, but the joint in the middle part of the pendulum swings wildly to and fro. The pendulum seems to switch from one kind of oscillation to another for no reason, even though it has been given apparently identical nudges.

* ***The crucial point is that the nudges are very slightly different to each other, and even though these differences are too small to notice they make a very noticeable difference in the behaviour of the pendulum. This is a form of chaos.***

* The same pendulum will also go through its entire repertoire of gyrations as it slows down, because although its speed is only changing gradually as it slows, at some points a small change in speed will flip it into a different pattern of oscillations.

chaos can be found throughout the natural world

KEY WORDS

SELF-ORGANIZED CRITICALITY: the way patterns appear in a system just before it tips over into chaos

CHAOS, COMPLEXITY AND LIFE

The most dramatic implications of chaos are only beginning to be investigated as we enter the new millennium. They link all of these ideas to the appearance of complexity in the Universe, and to the mystery of life and evolution. ***The key new discovery is that complex things exist 'on the edge of chaos', at the border between stability and chaotic behaviour.*** The neatest analogy to demonstrate this comes from PER BAK, a Danish physicist who describes complex systems as being in a state of 'SELF-ORGANIZED CRITICALITY'.

SELF-ORGANIZED CRITICALITY

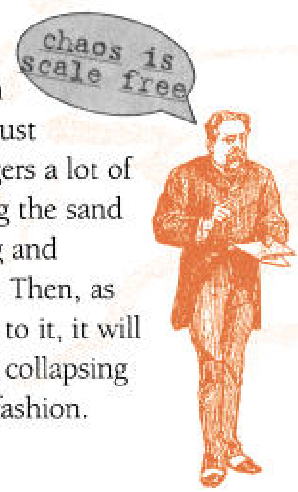
* All you need to demonstrate self-organized criticality is a tray of sand. If sand is spread out all over the tray, it is in a stable - and boring - state. Nothing interesting happens to it. But if you drop grains of sand onto the middle of the tray, one by one or in a slow stream, they build up a pile.

SCALE-FREE PHENOMENA

Earthquakes, large and small, are all generated by the same process, just like the avalanches produced by adding grains to a pile of sand. There's nothing special about large earthquakes, except for their size. This is good news for physicists, because it means you only need one theory to describe all kinds of earthquakes, ***whatever their size.*** Another way of describing this kind of phenomenon is to say that it is 'SCALE FREE'.

DRAMATIC BUILD-UP

* At first, this is just as stable and almost as boring as the rest of the sand. But at a critical point, little landslides and avalanches start to occur in the growing pile of sand. You reach a stage where adding just one grain of sand triggers a lot of avalanches, rearranging the sand pile into an interesting and complicated structure. Then, as you keep adding sand to it, it will build up again, before collapsing in the same dramatic fashion.



FEEDING OFF ENERGY

As we have just seen, a pile of sand can become a complicated and interesting structure on the edge of chaos. Yet each individual grain of sand automatically falls into place, in obedience to the laws of gravity and friction. A very simple set of physical rules has produced a relatively complicated pattern. There is, crucially, one other vital ingredient. We have been putting sand in from outside. ***This corresponds to a flow of energy through the system. What Bak and a few other physicists are saying is that simple laws feeding off a flow of energy can produce very complicated systems, without any other help at all.***

PUNCTUATED EQUILIBRIUM

*** Some of the most exciting applications of these ideas involve life itself. Charles Darwin's theory of evolution by natural selection describes a gradual process, with tiny changes accumulating from one generation to the next. But some evolutionary biologists - notably the Americans** Niles Eldridge **and** Steven Jay Gould **- argue that the fossil record seems to show long periods with little change going on, alternating with short intervals in which a lot of evolutionary change takes place. This is known as** PUNCTUATED EQUILIBRIUM.

each individual grain of sand obeys the laws of gravity and friction

the Red Queen has to move as fast as she can to stay in the same place

THE RED QUEEN EFFECT

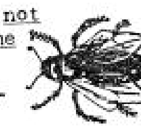
* Darwin's view of evolution implies that the whole web of life on Earth is constantly poised in an unstable state, like a growing sand pile. Everything in the ecosystem has to keep on evolving, to preserve its own niche, because everything else is evolving. This is known as the Red Queen effect, from the character in Lewis Carroll's *Through the Looking-Glass* who has to keep running as fast as she can in order to stay in the same place.

The peacock's tail

The splendid tail of the peacock may be a result of instability and the Red Queen effect. If – for whatever reason – peahens start to favour peacocks with large tails, then those peacocks will have more offspring than their less well-endowed brothers. Over many generations, this can produce the tails we see today.

EQUILIBRIUM RESTORED

well it's not eating me



* To see what biologists mean by the Red Queen effect, think of two different species living alongside one another. Suppose there are frogs that eat a certain kind of fly, which they catch by flicking out their tongues. If the frogs evolve a particularly sticky tongue, they will be adept at catching flies. The frogs will do well, and the flies badly, in the evolutionary stakes.

sticky-tongued frog