ENTROPY MAN

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Published by

VOCAT International Ltd
Harpenden
Herts
AL5 3ES
UK

ISBN 978-0-9562975-4-9

Front Cover: Getty Images.

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Preface

The seeds for this book were sown in the 1970s, four decades ago, when I was then working as group economist for the engineering corporation Babcock International Plc. At that time the group employed about 30,000 people in subsidiaries spread all around the world, engaged in the design, manufacture and installation of capital plant for a variety of industries, including nuclear & conventional power generation, coal mining, gas, chemicals & petroleum, steel, automotive, cement, construction and environmental engineering. Prior to that, my formal university education had included a degree in engineering at University of Bath and a Masters in management science, allied to student sandwich experience with Amalgamated Power Engineering *[now a subsidiary of Rolls Royce]* and ASEA Brown Boveri, Switzerland, followed by working for SKF, the Swedish bearing manufacturer, often considered to be a bell-weather of world economic output.

From the 1980s onwards I worked as director of a consultancy, and subsequently also as an expert witness to the Courts, which roles I continue to the present day. These experiences have taught me to maintain an enquiring, dispassionate and impartial mind regarding the complex workings of human endeavour, the natural world and changes arising thereof.

My particular research interests in those early years concerned the parallels between the disciplines of economics and thermodynamics *[the science of energy & heat]* and how they relate to each other, as a result of which I published two peer-reviewed papers on the subject in *Energy Economics [1979 & 1982]*. Subsequent to these I gave presentations to international gatherings of government ministers, energy industry executives and academia.

Not being based at a university however, and with no research grant at my disposal, my main thrust had been to make a living from consultancy and therefore, until more recently, opportunities to spend time on research were few. Nevertheless, by the turn of the millennium I was able to find time to return to some research and published another peer-reviewed paper in the *International Journal of Exergy [2007]*, followed up by several working papers on monetary aspects and energy models. Subsequently in 2009 I wrote a technical book on the subject, to bring together all the facets of the work into a coherent whole: *'Thermoeconomics – a thermodynamic approach to economics'*. The book was subsequently revised, corrected and added to, up to a third edition *[2012]*, covering topics such as production and consumption processes, employment, money, interest rates and bonds, energy resources, climate change and sustainability, and including more up to date statistics. It has now been superseded by this book.

Whilst not being tied to a university, government agency, industrial enterprise or other organisation has disadvantages in terms of recognition and time available for research, it does nevertheless have the advantages of freedom to investigate and pursue a course of enquiry of one's own choosing and of drawing conclusions independent of those that pay the piper or who may have pre-set agendas, however well-intentioned these may be.

The nature of the subject requires significant proof for economists and scientists to accept that similarities between thermodynamic and economic phenomena might imply more than just a passing analogy or isomorphism, and relations between the two disciplines have rarely been comfortable, with scientists sometimes having scant regard for the work of economists; and many economists believing that science has little to offer their discipline which, by its nature, can be thought of as anthropocentric rather than eco-centric. One eminent energy scientist advised me that he did not know of an economist who could follow a thermodynamic argument. Certainly a concept such as entropy means very little to most economists, still less to the man in the street – money is their language of communication. The latter is not, however, the language that Nature and the environment converse in.

This book is intended for a mixed readership of scientists, economists and those of an enquiring mind. It is a challenge therefore to convey the nub of the argument in terms that all can appreciate, with particular reference to the effects of potential problems such as 'peak resources', humankind's effect on the ecosystem and the maelstrom that would ensue should resource failure or climate change ever come about to a significant degree.

While some chapters, notably chapters 4 through to 8, do contain some mathematical expressions, explanatory points are included to guide non-mathematicians onwards. Formal proofs and derivations have been relegated to the notes on each chapter.
Although economic man may currently have the ascendency, he does not actually *'own'* the Earth. He is there on sufferance, and the Earth would

quickly forget him along the ecological timescale, should human civilisation fail or spoil the proceedings.

I am indebted to my wife Alison for all her support and for providing me with an atmosphere conducive to my research.

John Bryant

CHAPTER 1 SETTING THE ENTROPY SCENE

Prologue

In recent years continued growth in world human population and the advent of possible global resource shortages and climate and environmental difficulties has spawned an international industry of persons in academia, government agencies, commerce and the blogosphere proposing, refuting, failing to agree on, or just ignoring or putting off consideration of what may or may not occur in the future on planet Earth, and the time scale involved. The subject matter is one that is not going to go away in a hurry, and likely will continue to rear its head with regularity and perhaps increasing urgency.

Adding fuel to the fire, the financial crisis of 2008 saw the reputations of the discipline of economics and its practitioners take a hit in terms of ability to anticipate events based on accepted economic thinking concerning the way the world works. If the apparent divide between scientists and economists as to the worth of economic thinking had up to that point been wide, it had developed to a deep chasm as the cliff edge hove into view. It was openly stated by the Cambridge Trust for New Thinking in Economics that one of the problems that needed to be solved was the degradation of the planet and its atmosphere by over-consumption and over-production through the exploitation of resources in pursuit of monetary gain. And Robert John, Institute for New Economic Thinking, New York, opined that economics was at sea without an anchor, needed to overcome resistance to renewing the economics profession and would benefit from multi-disciplinary interaction to catalyse the evolution of economics.

When I set out to write this book, I had come to the conclusion that the science of energy and heat – thermodynamics – held one of the keys, which ultimately reflected in human economic activity and the world of money. I was struck, however, by the sheer difficulty in putting over in simple terms what is quite a complex subject, without putting off readers before they had got very far. My previous effort had resulted in a technical book full of equations, which might be intelligible to converted aficionados and mathematicians, but hardly makes for bedtime or holiday reading for the many. One eminent economist, reviewing my efforts, remarked to me that it might be preferable if there were no equations at all. The point was well made. Whether one is a addressing a scientist, an economist or just the person in the street, the guiding principle must be: *'keep it simple'* but not *'economise'* with the difficulties.

Rather than jump straight in at the deep end therefore, I have endeavoured in this chapter to illustrate by a series of scenes just how entropy affects everything that we humans have discovered about the world in which we live. While a scientist might just regard this as accepted knowledge, an economist might not be so trusting. Chapter 2, on the other hand shifts the balance, being concerned with a history of human development to the present time, which might accord more with an economist's anthropocentric view of the world in which we live. Succeeding chapters develop the theme stage by stage to link the world of economics to the world of thermodynamics.

Scene 1

My first introduction to the subject of thermodynamics was as a student at a lecture given by a jolly, rotund university don, who had brought along a video of a skit by the celebrated comedy duo Michael Flanders and Donald Swann. They were popular in the '50s and '60s with their revue *At the Drop of a Hat.* Flanders was a lyricist and Swann a pianist and composer. Flanders was wheelchair bound, having contracted poliomyelitis in 1943 when he was a young man. The particular rendering I saw was a jazzy setting of the first and second laws of thermodynamics, the lyrics of which went as follows, with Flanders doing the lecturing and Swann being the avid student:

> The First Law of Thermodynamics:
> Heat is work and work is heat
> *Heat is work and work is heat*
> Very good!
> The Second Law of Thermodynamics:
> Heat cannot of itself pass from one body to a hotter body
> *Heat cannot of itself pass from one body to a hotter body*
> Heat won't pass from a cooler to a hotter
> *Heat won't pass from a cooler to a hotter*
> You can try it if you like but you far better notter
> *You can try it if you like but you far better notter*
> 'Cos the cold in the cooler will get hotter as a ruler
> *'Cos the cold in the cooler will get hotter as a ruler*
> 'Cos the hotter body's heat will pass to the cooler
> *'Cos the hotter body's heat will pass to the cooler*
> First Law:
> Heat is work and work is heat and work is heat and heat is work
> Heat will pass by conduction
> *Heat will pass by conduction*

Heat will pass by convection
Heat will pass by convection
Heat will pass by radiation
Heat will pass by radiation
And that's a physical law
Heat is work and work's a curse
And all the heat in the Universe
Is gonna coooool down 'cos it can't increase
Then there'll be no more work and there'll be perfect peace
Really?
Yeah - that's entropy, man!
And all because of the Second Law of Thermodynamics, which lays down:
That you can't pass heat from the cooler to the hotter
Try it if you like but you far better notter
'Cos the cold in the cooler will get hotter as a ruler
'Cos the hotter body's heat will pass to the cooler
Oh, you can't pass heat from the cooler to the hotter
You can try it if you like but you'll only look a fooler
'Cos the cold in the cooler will get hotter as a ruler
That's a physical Law!
Oh, I'm hot!
Hot? That's because you've been working!
Oh, Beatles - nothing!
That's the First and Second Laws of Thermodynamics!

'First & Second Law' from 'At The Drop Of Another Hat' - Flanders & Swann © 1963 by permission of the Estates of Michael Flanders & Donald Swann.

The heat or energy content of a body is a function of both its mass and its temperature, and all that the First Law says is that when a closed system *[one that is not connected to another]* is taken through a cycle, the net work delivered to the surroundings is proportional to the net heat taken from the surroundings, and vice versa. We all have every day experiences of this transformation, from the steam in the kettle pushing up the lid, to the perspiration from working in the fields or exercising.

According to the Second Law of Thermodynamics, however, whatever the masses of individual bodies in a particular *closed* system, one cannot on its own transfer energy from one body at a low temperature to another body in the same system having a higher temperature; only the other way. It's the relative temperature difference between the two bodies that matters which determines the direction of heat flow from one to the other. There is no actual loss of overall energy content of the two bodies combined, but there is a reduction in the higher grade energy *potential* held by the hotter body which cannot be retrieved. Put a hot dish from an oven into a bowl of cold water, and the dish cools down and the water warms up a bit. Take the dish out and then neither of them returns to its previous temperature *[though the water might subsequently cool again if the air around the bowl is cold]*. Scientists measure this loss of energy potential as an increase in Entropy. Of course it is possible to *make* energy flow ‘uphill’, as in a refrigerator or heat pump, but this involves the input of work or energy from outside the system to do this, which then results in an overall net loss of energy potential and a net increase in entropy.

The idea of entropy originally stemmed from the work of a number of physicists including Sadi Carnot, Rudolf Clausius, Willard Gibbs, James Maxwell and Ludwig Boltzmann *[1844 – 1906]*. Such was Boltzmann’s fame that on his death his logarithmic equation for entropy was inscribed on his tombstone.

$$S = k.\log W$$

In his honour, the constant **k** is known as the Boltzmann constant *[the kinetic energy of a gas molecule per degree of a scale of temperature, 1.3807 x* 10^{-23} *Joules/ºK]*. **W** stands for a German word, *Wahrscheinlichkeit*, meaning the probability or frequency of occurrence of an event. The concept of entropy has gained general acceptance and use in many fields of study, including classical thermodynamics, gas dynamics, statistical mechanics, chemical thermodynamics, semiconductor physics and biochemistry. The term has also been adopted in the world of information theory, owing to the close resemblance of a mathematical formula developed by Claude Shannon *[American mathematician, engineer and cryptographer (1916 – 2001)]* to that used in thermodynamics. Everything that humankind has discovered about the universe so far appears to conform to the Laws of Thermodynamics.

A little nearer to home than the universe, the Sun *[one hesitates to call it ‘our’ sun – we humans do not own it]* is a G-type main sequence star *[a yellow dwarf]* that continually radiates short-wave energy to its planets and beyond into space. The Sun has a diameter of about 1.4 million km *[more than a hundred times that of the Earth. One could fit 1.2 million Earths inside the Sun]* and has a temperature at its core of about 15,600,000ºK *[Kelvin: 273ºK = 0ºC]*, but only about 5,800ºK at its surface. Taking into account the distance of the Earth from the Sun of about 150 million km, then the amount of short-wave radiant energy from the Sun hitting the Earth at any time is of the order of two billionths of that the Sun radiates elsewhere.

Considering only the Sun and its surrounding space, then the entropy level of this system is forever increasing as the Sun radiates energy at 5,800ºK into space, where the residual microwave radiation is at about 3ºK, close to absolute zero. One day, perhaps billions of years in the future, the Sun may change into a red giant before dwindling to a 'white dwarf'.

The Earth by contrast, with a diameter of only 12,800 km, has a temperature at its core of about 7,500ºK *[hotter than the surface temperature of the Sun]* and an average atmospheric temperature at its surface of approaching 288ºK *[15ºC]*, with a variation of between 184 – 331ºK, depending upon where one is standing – at the poles or the equator, northern or southern hemisphere, land or sea – and when – day or night time, winter or summer. Similar to the Sun, the Earth radiates heat outwards into space, but in the form of long-wave radiation *[of lower intensity than that from the Sun]*, either directly from its surface or indirectly via its atmosphere.

Variations in the surface temperature of the Earth are thought to be a function of a number of cyclical factors, including the Earth's axial tilt, *[which is on average 23.5º]*, axial precession *[the Earth wobbles slightly on its axis of rotation like a spinning top]*, orbital shape round the Sun *[from nearly circular to mildly elliptical]*, apsidal precession *[the orbit itself swings around the Sun – a bit like swinging a hula-hoop]* and orbital inclination. These cyclical factors – known as Milankovitch cycles – have different lengths, from around 21,000 years up to 400,000 years, affecting cycles of glacial advances and retreats ending with the Holocene interglacial which began 12,000 years ago, within the current Pleistocene ice-age, which began around two and a half million years ago.

Other significant factors influencing atmospheric temperature at the surface of the Earth include variations in the Sun's energy output, sun spots, volcanic eruptions on the Earth's surface arising from activity below the crust, and atmospheric composition, in particular the amount and position of greenhouse gases, such as water vapour, carbon dioxide, methane, ozone and nitrous oxide. The latter help to provide a warming effect to the surface of the planet, and without them the surface would be around 33ºK cooler, at 255ºK or -18ºC. At this level, much of life on Earth could not exist. Over the period of time from which we humans have information about it, through ice-core samples, tree rings and other methods of measurement, there has been an approximate net energy balance between the incoming and outgoing radiation to and from the Earth, such that the average surface temperature has varied up and down by a few degrees.

Entropy production is central to the Earth's atmospheric and ocean climate systems, which are essentially non-equilibrium systems forever seeking steady state, maximum entropy production positions, governed principally by changing heat fluxes as the Earth spins and orbits the sun. Researchers of this phenomenon include Paltridge, Ozawa, Jenkins, Goody, Kleidon, Pascale, Lorenz and others. Atmospheric-ocean circulation models, such as the Met Office Unified Model, contain equations that embody the Laws of Thermodynamics in their structure.

Taking the Sun, the Earth and the surrounding space as the system, then nothing in this assessment contravenes the Laws of Thermodynamics. Energy does not of its own flow from the colder surfaces of the Sun and Earth to their respective hotter centres; only the other way, from their centres to their surfaces and then into space, or from the Sun to the Earth and then into space. The net entropy of the system forever increases.

By extension it is reasonable to conclude that the Laws of Thermodynamics apply also to the other planets within the Solar System with respect to the Sun, and to those planets orbiting other stars in the galaxy and beyond. Jupiter, the largest of the gas giant planets in the Solar System for example, has a core temperature in the region of 24,300ºK, and a temperature at the surface of its clouds of only 128ºK *[-145ºC]*. Even at this temperature it actually radiates more energy into space than it receives from the Sun, as do the other gas giants Saturn, Uranus and Neptune. They are gradually losing energy potential, with a resultant rise in entropy. Venus by contrast, the closest neighbouring planet to Earth, has a core temperature estimated at about 5,200ºK. It has an atmosphere composed mainly of carbon dioxide and a little nitrogen, laced with cloudy layers of reflective sulphur dioxide/ sulphuric acid creating a strong greenhouse effect. It has a mean surface temperature of 735ºK at a pressure of 92bar *[equal to 92 times the atmospheric pressure on Earth at sea level]*. Mars, the other close neighbour to Earth, is quite small, having a diameter of 6,800 km, a little over half that of Earth. It has a very weak magnetic field and it is thought that its core may now be solid, consisting mainly of iron. If so its core temperature may only be at about 1800ºK. It has a very thin atmosphere, mostly of carbon dioxide, at a pressure of less than 1% of that of Earth, and an average surface temperature of only 210ºK.

Scene 2

Accepting that the Earth itself operates in keeping with the Laws of Thermodynamics, it might be expected that everything on it too has likewise operated and evolved in a manner in keeping with those same laws. Turning towards the micro-state therefore, consider the reaction here on Earth when ice turns to water and water evaporates and turns to steam. Leave ice out in warm air and it melts; boil some water in a pot over a fire and it first warms up and then evaporates. In both cases heat has been supplied, the first from the warm air, and the second from the fire. It's every schoolchild's knowledge that one has to supply some heat for these transformations to take place, as in the following equation:

$$H_2O\text{ (ice)} + \text{heat} \rightleftharpoons H_2O\text{ (water)} + \text{heat} \rightleftharpoons H_20\text{ (water vapour/steam)}$$

The equation is stated with reversible signs, to show that it is possible to move up and down the hierarchy. Without a supply of heat it is not possible to move upwards in the hierarchy, and without a surrounding sink of cold air or the use of a refrigerator it is not possible to withdraw heat and move downwards.

Putting it rather starkly at the global level, turn off the short-wave radiant heat received from the Sun and, over time, according to the Laws of Thermodynamics, long-wave energy would radiate from Earth into cold space and then any remaining clouds would gradually fall as rain and any remaining land-based water and the oceans would gradually cool down and turn to ice, with a corresponding irrevocable generation of entropy. The end state of the reaction *[including the Earth and space in the system but excluding the Sun]* is that we might all be frozen solid, with an ice sheet covering the whole planet.

Thankfully the Sun continues to shine and we have two reactions having opposing flows of radiant energy, one from the Sun to the Earth, and the other from the Earth into space. The natural state of affairs is that these flows will continue to take place, such that some equilibrium level of surface temperature of the Earth will continually be sought over time, but dependent also upon any changes in other impacting factors as they occur.

Continuing at the micro-state, at school in chemistry we are taught about chemical reactions, and how in some cases a reaction can proceed only in a forward direction to form products, but in other cases a reaction can proceed in either direction, forwards to products, or backwards to initial reactants.

As an example of the latter case, adding water to anhydrous copper(II) sulphate, which is white in colour, produces hydrated copper(II) sulphate, which is blue in colour.

$$CuSO_4 \cdot 5(H_2O) \rightleftharpoons CuSO_4 + 5H_2O$$

Heat the result up however and the colour changes back to white as the water is removed. Thus varying the ambient conditions of temperature and water in the surrounding air can affect the relative position. Such reactions can be thought of as constantly reacting in both directions, with particular conditions favouring the subsequent relative equilibrium position reached.

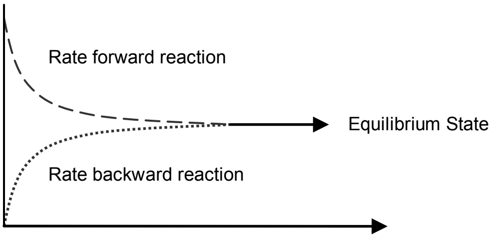

Figure 1.1 Forward and Backward Reactions.

A uni-directional reaction, however, is one that can only proceed in a forward direction, and cannot be undone directly. An example is the combustion of methane *[a component of natural gas]* to produce water and carbon dioxide:

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O + \text{Heat}$$

The study of chemical reactions is particularly important when we come to consider economic systems, and the principle which governs such reactions is known as the Le Châtelier Principle *[named after Henry Le Châtelier, a French chemist (1850–1936)]* which states:

"If a change occurs in one of the factors under which a system is equilibrium, then the system will tend to adjust itself so as to annul as far as possible the effects of that change".

It is not asserted that a system *will* attain equilibrium, only that it will continually seek to proceed to such a position. In fact such a system will not work without being in a state of disequilibrium. Thus if we disturb an equilibrium position, by increasing or decreasing the amount of a product or one or more of the reactants, or by changing the temperature or other impacting factor, then the system reactions will effect a move either to the left or to the right in the equation so as to adjust to a new equilibrium position. At the new equilibrium position any forward momentum is matched by a reverse momentum and the system has *maximised its entropy level,* with no further change in entropy occurring.

One can extend this analysis to a dynamic situation such as a flow of inputs per unit of time, matched by a flow of outputs per unit of time, in which case the system maximises its level of entropy production per unit of time.

Besides the traditional laboratory picture of liquid compounds being mixed together, the same analysis also applies to mixtures of gases, but in such cases, as well as temperature, a scientist has to take account of the fact that gases can expand or contract according to their pressure. An example of a gas reaction is that of carbon monoxide reacting with oxygen to form carbon dioxide.

$$2CO + O_2 \rightleftharpoons 2CO_2 + \text{Heat}$$

Ordinarily, there is a release of heat in the forward reaction as indicated in the above equation – what is known as an *exothermic* reaction. But if sufficient heat is applied to molecules of CO_2 then the reaction can be made to proceed in the reverse direction – what is known as dissociation *[literally coming to bits]*. This reaction is an *endothermic* reaction, which absorbs heat rather than producing it. Thus, by varying the temperature and pressure of the mixture of the gases, it possible to vary their relative proportions and the equilibrium position between them.

The reader may note rather obviously, however, that it is not just the fact that some substances can react with each other according to particular conditions, but that the level of reaction depends also upon the quantities available. For instance, in the equation for combining carbon monoxide with oxygen to produce carbon dioxide, if there was only a small amount of free oxygen available, then no matter how much carbon monoxide was supplied in the forward path, the reaction would come to a halt quite quickly. It depends therefore upon the relative amounts on both sides of the equation as to how a reaction takes place, not just conditions of temperature and pressure.

Scene 3

Advances in biochemical science in recent decades, such as the discovery of DNA, have shown that the building blocks of life are made up of complex strings and arrangements of molecules, featuring particular groups of atomic elements, carbon, hydrogen, nitrogen, oxygen and others, and that these building blocks also react and develop in particular ways that mimic the chemical reaction processes that we have so far discussed.

Living things are characterised by a high degree of structure and assembly *[scientists call this an ordered state]* and typically exhibit a property of high energy potential and low entropy. A biochemical example of this is the folding and unfolding of proteins. A polypeptide for example *[a long continuous and un-branched peptide chain that can be bent and twisted into countless conformations – a disordered state]* becomes much more restricted *[ordered]* in its orientation when it has folded into a protein. This results in a *negative* change in entropy to the protein from the free energy potential that has been used up in the process. Biochemists use entropy as a tool to comprehend spontaneous change in such cases.

It is important to note, however, that these changes do not occur in isolation. Such organisms are not closed systems, but are connected to myriads of others within a small amount of tissue. Thus an organism such as a protein, by taking on additional order for itself and decreasing its entropy, disperses energy and creates disorder and an increased level of entropy elsewhere outside the organism, such that the net entropy combined constitutes an overall increase, in line with the Second Law of Thermodynamics.

Trees, for example, are high order organisms that obtain energy by extracting low entropy short-wave solar energy directly from the Sun through photosynthesis, consuming carbon dioxide from the atmosphere and extracting water and other nutrients from the topsoil *[which itself is an ecosystem containing microbiota, organic matter and larger organisms]* and thereby create sugars for their succour before releasing oxygen back into the atmosphere.

$$6CO_2 + 6H_2O \longrightarrow (CH_2O)_6 + 6O_2$$

Thus trees are able to maintain a low level of entropy for themselves, releasing heat and high entropy waste products. The waste heat is subsequently released into the atmosphere and then via long-wave radiation into space.

Animals constitute even higher level ordered organisms compared to plants and trees, and maintain their low level of entropy by consuming plant life *[or eating something that eats plants],* combining it with oxygen from the air ingested via their lungs, and expelling/excreting high entropy waste products, including CO_2, into the biosphere and atmosphere. Taking into account the overall system, not just the animals, net entropy tends to increase. The same principle applies to fish, except that they extract oxygen that is dissolved in water by passing the water over their gills. At the same time they excrete carbon dioxide from their gills back into water.

Austrian Nobel prize winner Erwin Schrödinger *[1881 – 1961]* opined that living organisms maintain themselves at a fairly high level of orderliness *[low level of entropy]* by continually sucking orderliness from their environment. Thus the life process tends to augment the production of entropy in the universe.

Life on the surface of the Earth is possible because the surface temperature is high enough to allow structure creating systems to evolve, but low enough to ensure that they are not burnt out. It can cease if a relatively small temperature change occurs in either direction.

Until the 1970s, life on Earth as we humans had understood it was believed to be entirely dependent on energy received from the Sun. However, during a deep-sea dive in 1977 to the Galapagos Rift by the exploratory submersible Alvin, scientists discovered colonies of tube worms, clams, crustaceans, mussels and other creatures around undersea volcanic hydrothermal vents known as ‘black smokers’. These creatures survived without access to sunlight. Instead of plants they consumed bacteria that derived their energy from the oxidation of chemicals such as hydrogen and hydrogen sulphide that bubbled up from the Earth’s interior.

Thus life was shown to be not necessarily sun-dependent, but only required water and an energy-gradient to exist – *‘from a hotter to a cooler’* as Messrs Flanders and Swann would have said. And as we have already set out so far in this book, using up an energy gradient implies a release of entropy to the environment, in excess of the reduction in entropy achieved by living things for themselves.

This has opened up the question again as to the relative probability of life existing elsewhere in the universe. James Lovelock, the well-known progenitor of the Gaia principle, when asked by NASA as to what they should look out for when searching the planet Mars for life, replied that he'd look for an entropy reduction since this must be a general characteristic of living things. Indeed 'astrobiology' as it is called has been the focus of a number of NASA and European Space Agency Solar System exploration missions, such as the Viking, Beagle 2, Phoenix and the recent Curiosity probes. Further missions are likely in the future, perhaps to the frozen moons of Jupiter.

Scene 4

That life maintains a low level of entropy for itself by continually creating an entropy increase outside itself, few scientists would dispute. It is a step further, however, to say that the process of evolution itself has connections with or abides by the Laws of Thermodynamics.

We are all familiar with the idea of natural selection, first set out by Charles Darwin in his book *The Origin of Species by Means of Natural Selection,* following his 5-year voyage round the world on HMS Beagle, ending in 1836. Indeed, nearly two centuries later, the idea that life forms evolve over time has mostly been accepted.

Darwin's theory was based on a number of observations: that there is variation within a species, that offspring inherit some characteristics of their parents, that more offspring are produced than survive to maturity *[as a result of disease, predation or competition]* and that populations are usually fairly constant in size. He concluded that individuals that were better adapted to their environment could compete better, could survive longer and reproduce more – *survival of the fittest and natural selection.*

In general there are three kinds of natural selection among species:

- Directional – as a result of a change in the environment.
- Normalising – where the environment does not change and species become centred about a 'norm'.
- Diverging – where an environmental change impacts on selection to favour two extremes of species characteristics.

An interesting recent contribution in support of the Darwinian theory of evolution is that of the E-coli long-term evolution experiment, led by Richard Lenski *[American evolutionary biologist]*, that has been on-going since 1988, tracking genetic changes in twelve initially identical populations of Escherichia coli bacteria. By 2010 the populations had reached 50,000 generations, with all twelve of the populations showing an increase in size over the period. Of particular interest, however, is that at generation 33,127 the experimenters discovered that one sample had mutated to be able to cope with a citrate environment, where previous generations had not been able to do so. This brings to mind both the creatures found in the Galapagos Rift, referred to earlier, that had found a way to do without sunlight, and a further example of bacteria and other microbes which, through random mutations, can develop resistance to antibiotics, so that the latter can cease to be effective.

A key to onset of species change is therefore that of change in environment and habitat *[including also resources and the wherewithal to take advantage of them]*, which could be either positive or negative – the former offering more chances to develop and increase, and the latter potentially reducing the survivability of a species, and potentially those others around it also affected by the change. Progress over time in nature appears to favour the evolution of adaptive biological structures, of which Homo Sapiens is the highest order living thing on Earth. Effectively life seeks to follow a path of maximum entropy gradient, choosing the first available path in terms of time that does this, but if this subsequently proves not to be fruitful or provide further opportunities, it seeks another path or endeavours to adapt itself in some way in line with prevailing constraints, but if all these strategies fail it can eventually become extinct.

There are literally millions of species resident here on Earth. Plants, insects and invertebrates are amongst the most numerous eukaryotic species; and of the 63,000 or so vertebrates, fish constitute about half and mammals about 5,500. Bacteria and archaea, which are termed prokaryotic species, possibly number billions in variety. The International Union for Conservation of Nature maintains a list of numbers of species that are critically endangered, endangered or vulnerable to becoming extinct. Birds have been among those in decline since 1988.

Following the work of Rosalind Franklin and the discovery of DNA by James Watson & Francis Crick, there has been quite a bit of research carried out on the use of entropy as a tool in human genome studies. The particular variant of entropy formula used in this case is that of the Shannon Entropy, developed in information theory by Claude Shannon, mentioned earlier in this chapter, and quantifies the ‘expected’ value of information contained in a message.

All entropy formulae are both probabilistic and logarithmic in form. By probabilistic we mean that we cannot know precisely what a value may be at any instance in time, we can only estimate a most likely value. And by logarithmic we mean that it is non-linear in shape, as in the Boltzmann equation illustrated at Scene 1 of this chapter. In the case of information theory, the logarithmic factor is expressed either to the base 2, with entropy being measured in *'bits'*, or it is expressed to the natural log base **e**, with entropy being measured in *'nats'* and with the constant **k** becoming equal to 1.

For interested readers, a selection of research articles is listed in the bibliography and references for this chapter, covering such subjects as entropy applied to body size, metabolic rate, life-span, analysis of the genome code, natural selection for least action, sequencing, diversity, self-organisation and entropy reduction in a living cell. The writer does not profess to be an expert in these areas but clearly as time goes on human knowledge is gathering pace in the fields of evolution and genomics.