Design and Information in Biology

From Molecules to Systems

Design and Nature

Objectives

Our understanding of the modern world is largely based on an ever increasing volume of scientific knowledge. Engineering designers have at their disposal a vast array of relationships for materials, mechanisms and control, and these laws have been painstakingly assembled by observation of nature. As space activity accustoms us to cosmic scales, and as medicine and biology to the molecular scale of genetics, we have also become more aware of the rich diversity of the structural world around us.

The parallels between human design and nature has inspired many geniuses through history, in engineering, mathematics and other subjects. Much more recently there has been significant research related to design and invention. Even so, current developments in design engineering, and the huge increase in biological knowledge, together with the virtual revolution in computer power and numerical modelling, have all made possible more comprehensive studies of nature. It is these developments which have led to the establishment of this international book series.

Its rationale rests upon the universality of scientific laws in both nature and human design, and on their common material basis. Our organic and inorganic worlds have common energy requirements, which are of great theoretical significance in interpreting our environment.

Individual books in the series cover topics in depth such as mathematics in nature, evolution, natural selection, vision and acoustic systems, robotics, shape in nature, biomimetics, creativity and others. While being rigorous in their approach, the books are structured to appeal to specialist and non-specialist alike.

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Design and Information in Biology

From Molecules to Systems

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Dedication

Dr. Mark J. Randall
born 6th April 1971
died 21st September 2000

This book is dedicated to the memory of Mark J. Randall, the author of the chapter entitled ‘Insect Observations and Hexapod Designs’.

Shortly before his untimely death, Dr. Randall enthusiastically agreed to provide a chapter on walking mechanisms, based on nature, at a Sussex summer garden party in 2000 where he met one of the editors. Our plans for a book series in Design & Nature were in their early stages at this time but the standard of Mark’s work was so high that we sought to reproduce a chapter from his own book in lieu of the one he was unable to complete. Mark worked on artificial intelligence applied to how robots might ‘learn’ to traverse difficult terrain, and he was particularly interested in the de-mining of war zones, a concern consistent with his Christian faith.

Mark was born in Pontypool, Wales. He studied at Imperial College, London, gaining a 2.1 honours degree in Theoretical Physics, followed by a PGCE at Magdalen College, Oxford. He obtained his PhD from the University of the West of England in 1999 where he was a Senior Lecturer. He has left behind his wife Emma and three young daughters, Deborah, Anna and Ellena. Emma has kindly allowed us to reproduce the material of the chapter.

We would like, finally, to thank Professor Carlos Brebbia at the Wessex Institute of Technology for suggesting this dedication.

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Design in nature – introduction to the series

Michael W. Collins
Brunel University, UK.

Prologue

> *almost a miracle* [Cecil Lewis, 1, p. 126]
>
> *almost miraculously* [Stuart Kauffman, 2, p. 25]

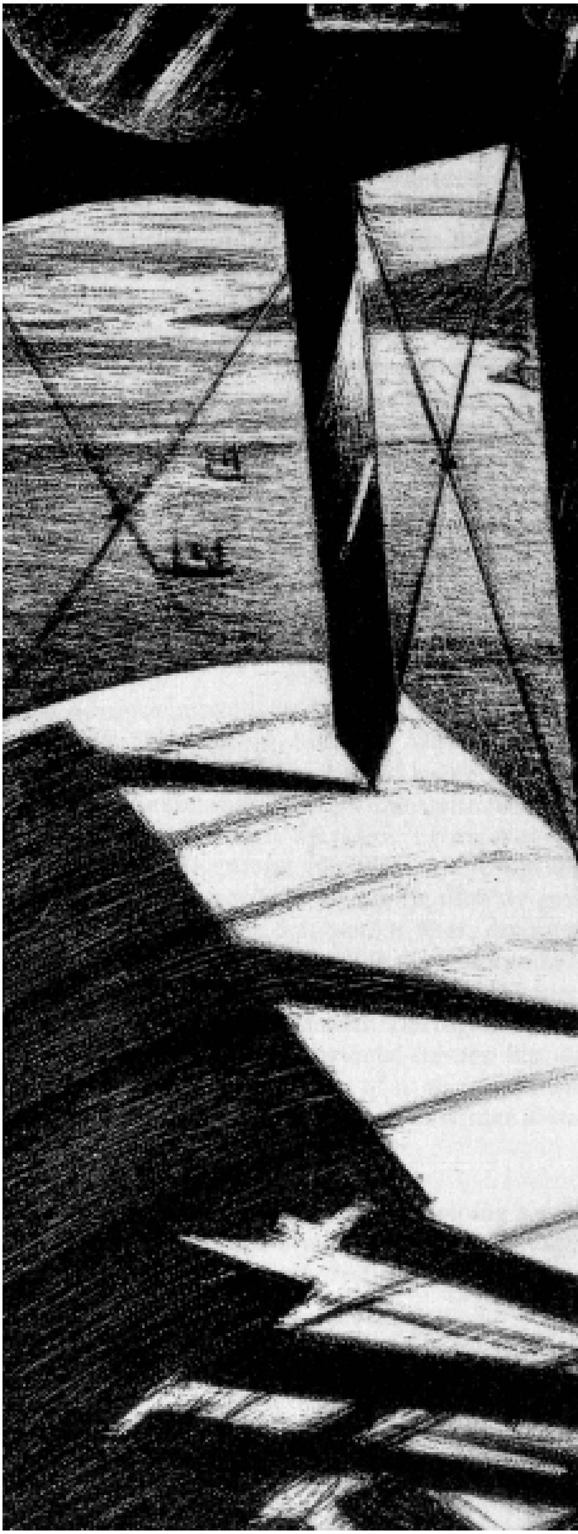
‘It was a beautiful evening’ wrote Cecil Lewis [1] of the day in 1917 when he took a new SE5 on a test flight. ‘At ten thousand feet the view was immense, England quartered on its northern perimeter at twenty two thousand feet, Kent was below me …… for a second the amazing adventure of flight overwhelmed me. Nothing between me and oblivion but a pair of light linen-covered wings and the roar of a 200-hp engine! …… It was a triumph of human intelligence and skill – almost a miracle’ (See Plate 1).

Cecil Lewis was only 19 years old at the time, having left the English public school Oundle, in order to join the Royal Flying Corps in the First World War.

Almost 40 years later, in happier times than those of Cecil Lewis, as another ex-schoolboy I was ‘filling in time’ with a Student Apprenticeship before going to University. My very first job was as ‘D.O. Librarian’ in an aeronautical engineering drawing office. The circumstances may have been prosaic, but one feature always intrigued me. At the apex of the very large pyramid, at the top of every document distribution list, was the Chief Designer. Of course, I never met him or even saw him, but to me his title expressed the fount of authority, intelligence and creativity, the *producer* of ‘almost miracles’ for the 1950’s.

‘Almost miracles’ mean different things to different people. Another 40 years brings us to a new millennium, to Stuart Kauffman [2] writing in 2000. Kauffman, a highly regarded American biologist ‘is a founding member of the Santa Fe Institute, the leading centre for the emerging sciences of complexity’ [2, cover blurb]. In discussing DNA symmetry and replication, he says [2, page 25]: “It seems to most biologists that this beautiful double helix aperiodic structure is almost miraculously pre-fitted by chemistry and God for the task of being the master molecule of life. If so, then the origin of life must be based on some form of a double-stranded aperiodic solid” (see Plate II). Yes, Kauffman is in the heady business of studying life starting ‘from non-life here, or on Mars’.

We have reflected Cecil Lewis’s and Kauffman’s near miracles in Plates I and II. In the case of Cecil Lewis he was still in the first flush of man’s ability to fly. Not for him the necessity of filing a flight plan. Like the *natural* fliers, the birds, he could move at will in three-dimensional space.

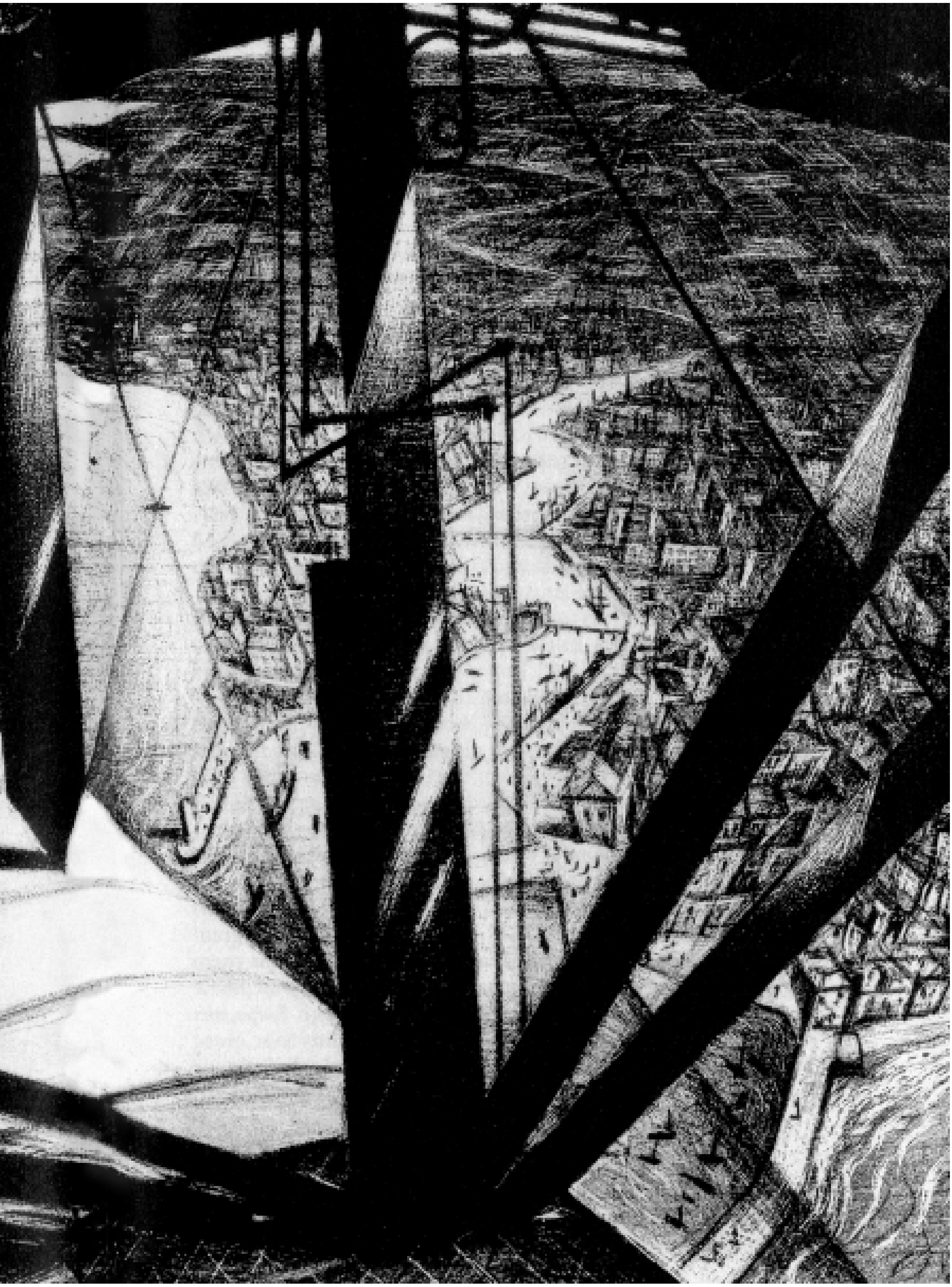


However, even then, he could far out-fly them, whether in speed or in height. Stuart Kauffman, however, moves about in multi-dimensional space. *His* is a 'fitness landscape in … thirteen-dimensional parameter space' [2, p. 70].

We do need, at the same time, our sense of wonder to be well informed. Of course, Cecil Lewis's near miracle has been totally replaced, by Jet Propulsion, by travel to the moon, and now by planetary exploration. In the same way, while the thirteen-dimensional space of Kauffman may well impress many of his readers, and the eleven-dimensional space of Stephen Hawking [3] was obviously expected to impress the average UK Daily Telegraph readers, in engineering terms this is a standard practice. Two of the Series Editors [MAA and MWC] started to consider [4] the problem of *visualisation* of complex data. This included reference to the optimisation of nuclear power station design [the UK Magnox system], which used a contour-tracking procedure focusing on 30 major parameters out of about 100 parameters in total [Russ Lewis, 5].

We conclude this prologue with the realisation that nature, nature's laws and the use of nature's laws in human design all have the capacity to enlighten, inform and inspire us. This series will have achieved its end if it demonstrates only a small part of that capacity.

Plate I: 'It was a triumph of human intelligence and skill - almost a miracle'. 'View from an aeroplane' [1, p182-183] (Reproduced by permission of the Victoria and Albert Museum Picture Library).



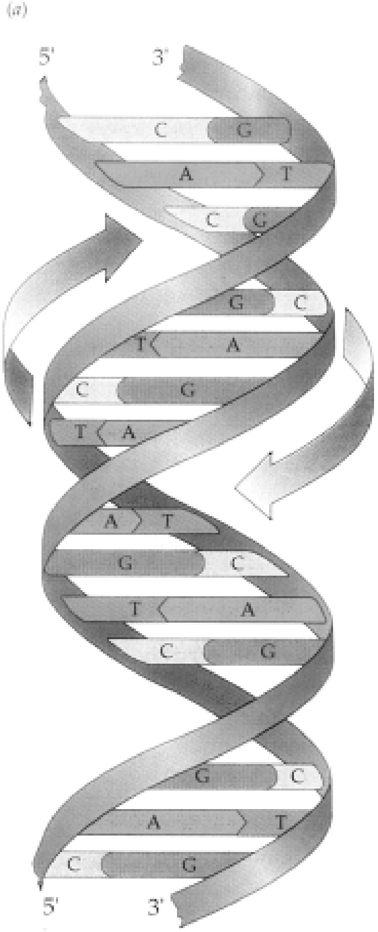


Plate II: 'This beautiful double helix.....structure is almost miraculously pre-fitted....'

DNA is a double helix

Plate II: Watson and Crick proposed that DNA is a double-helical molecule. The helical bands represent the two sugar-phosphate chains, with pairs of bases forming horizontal connections between the chains. The two chains run in opposite directions; biochemists can now pinpoint the position of every atom in a DNA macromolecule.
(Reproduced by permission from *Life. Volume 1 the Cell and Heredity*. 4th Edition by W.K. Purves, G.H. Orians and H.C. Heller, p246, Sinauer Associates, W.H. Freeman & Co.)

Research Field of John Bryant, Series Co-Editor

John Bryant's research is mainly concerned with the initiation of DNA replication - the very start of the process of copying the genome. It is far more complicated than we envisaged even ten years ago.....indeed it has a beautiful and almost awe-inspiring complexity. Each stage is tightly regulated so as to ensure that the cell only duplicates its genome at appropriate times. As we understand more about these control mechanisms we can only wonder at, and about, the evolutionary processes through which they developed.

Nature and engineering

The beavers have practised civil engineering since they became a species
[Eric Laithwaite, 6, p. 231]

Intellectually, the engineer and the artist are not far apart [Michael French, 7, p. 179]

The subject area of our series has great public interest and popularity, if we take the increasing number of publications as evidence. But this needs clarifying. Like Eric Laithwaite having to make a choice at Grammar School [6, p. xi] we might be forgiven for supposing that *our* subject is either biology or physics. On thinking more carefully, we could define our subject as the commonality of the laws of physics, in the natural [biological] and man-made [engineered] worlds. This is nearer the truth.

In the event, Eric Laithwaite chose physics. He went on to become a noted engineer and inventor, being awarded, in 1966, the Royal Society S.G. Brown Medal for Invention. So, for *him*, the beavers were engineers, not scientists.

In the same way, Michael French compares biologists, not with physicists, but with engineers and architects [7, pp. 1–2]. His book, like Laithwaites', is engineering-oriented – 'about design for function, and invention' [7, p. xvii].

So, despite so many of the recent publications being by biologists and physicists, we have chosen two engineers to start our Introduction. In fact, their approach represents a relatively new exploitation of the laws of physics, and materials science, as used in the biological design of living organisms. This points us in the direction of 'biomimetics' which is a recent concept involving the application of biological materials in engineered systems [p. xvii, Vol. 4 of this Series].

Laithwaite and French raise other issues. The first is noticeable by its absence. Those readers whose discipline is chemistry or chemical engineering might wonder if the subject has been 'air-brushed out'. Of course not – if no chemistry, then there is no DNA, no design in nature. We have already quoted Kauffman in this regard.

The next, lightly touched on by French [7, p. 235], as also by Kauffman [2, p. 24], is the question of what is meant by 'beauty'. While French strictly connects it to function in design, we will connect it to art in general, and find it is an integral part of our overall study. As French implies, the engineer and the artist are good friends.

The final issue is the question of mathematics. Whereas French [7, p. 291] rather pejoratively quotes from Bondi that 'mathematicians are not particularly good at thinking … good rather at avoiding thought', Laithwaite is obviously fascinated by the whole thing. For instance, he, like me, is highly intrigued [who isn't] by the identity.

$$e^{i\pi} = -1$$

In the same vein, he deals in some detail with the topics of 'ideal shape' in the form of the golden section [6, pp. 199–202] of Fibonacci numbers, and of helices in plants. He points out that the logarithmic spiral [6, pp. 201–202] retains its shape with growth, coinciding with French's reference to gnomonic shell growth [7, p. 273].

So then, two engineers have introduced our discussion. We now have to explain what *we* mean by the word '*design*'.

Design in the mainstream

> *The buttercups and the locomotive show evidence of design*
>
> [Michael French, 7, p. 1]

> *I am, in fact, not so much concerned with origins or reasons as with relations or resemblances*
>
> [Theodore Cook, 8, p. 4]

We can best describe our use of the word ‘design’ by the acronym *wysiwyg* – what you see is what you get. Our ambition is to explore fully the richness of the ‘design of the buttercup’ and the comparison of the designs of nature and engineering, all in the same spirit of Michael French. We shall avoid all issues like ‘despite there being ‘evidence of design’ we do not believe …’ on the one hand, or ‘because there is evidence of design, we therefore believe …’ on the other. The point has been put more elegantly by Theodore Cook, as long ago as 1914 [8, above].

So, we do not, as does Richard Dawkins, use the expression *designoid*. In ‘Climbing Mount Improbable’ [9, p. 4], he addresses this very point. ‘Designoid objects look designed, so much so that some people – probably, alas, most people – think that they are designed’. So he uses designoid because of his antipathy to theism – ‘no sane creator … would have conceived on his drawing board’ he says on p. 121 [9]. In our use of the word design, however, we retain Richard Dawkins’ friendship, with his pitcher plant giving ‘every appearance of being excellently well designed’ [9, p. 9], and his approbation of engineers – ‘often the people best qualified to analyse how animal and plant bodies work’ [9, p. 16].

However, in using the word design, neither do we mean *conscious design*, *intelligent design*, *[intelligent] design or [   ] design* … merely design.

Typical use of these explanations is given as follows, with the understanding that ‘conscious design’ is rather an archaic description:

i.	Conscious design	[Cook, 8, p. 4], [Ruse, 10, p. 44]
ii.	Intelligent design	[Miller, 11, p. 92], [Ruse, 10, p. 120]
iii.	[Intelligent] design	[Miller, 11, pp. 93, 126], [Ruse, 10, p121]
iv.	[ ] design	[Behe, 12, p209], [Dembski, 13, Title]

The last-mentioned author, William Dembski has, sadly, suffered for his beliefs, as explained in ‘The Lynching of Bill Dembski’ [14]. Nevertheless, in fairness, Dembski separates out the ideas of ‘design’ and ‘designer’, as this extended quote makes clear:

> ‘Thus, in practice, to infer design is typically to end up with a ‘designer’ in the classical sense. *Nevertheless, it is useful to separate* [MWC’s italics] design from the theories of intelligence and intelligent agency’ [13, p. 36].

While the use of the word ‘design’ here may not be coincidental with that of Dembski, yet the act of separation is crucial, and consistent with the rationale for this Series. By using *wysiwyg* we are trying to retain the friendship of both Dawkins and Dembski and, further, to retain and parallel their common enthusiasm and commitment. In the Series, then, we seek to stay in the mainstream of all aspects of design in the natural and man-made worlds, stressing commonality rather than controversy and reconciliation of differences rather than their sharpening. In that spirit, where necessary, current controversies will be openly discussed and separate issues carefully identified.

Even this brief discussion has shown that the concept of 'design' is both subtle and wide-ranging in its connotations. We now address three specific aspects which are sometimes ignored or even avoided, namely, *mathematics*, *thermodynamics* and *history*.

Mathematics

We like to think mathematics was discovered, not invented
Prof. Tim Pedley, verbal, Salford, 1998

The universe appears to have been designed by a pure mathematician
[James Jeans, 15, p. 137]
quoted in [Paul Davies, 16, p. 202]

Now while the commonality of scientific laws in the natural world is generally accepted, the fact that the world is also mathematically *oriented* is less well understood. Of course, the concept of mathematics being somehow 'built in' to nature's structure is highly significant in terms of our rationale – nature's designs being parallel to man-made designs. Paul Davies expressed this concept in various telling phrases. In 'The Mind of God' we read '… all known fundamental laws are found to be mathematical in form' [16, p. 84]. 'To the scientist, mathematics … is also, astonishingly, the language of nature itself' [p. 16, 93], and as the heading for Figure 10 [p. 109] 'The laws of physics and computable mathematics may form a unique closed cycle of existence'.

In fairness, it should be added, as does Davies, that this approach is not universally accepted, and mathematicians have 'two broadly opposed schools of thought' [16, p. 141]. In the chapter on mathematics in nature' in *this* Volume the issue is dealt with more fully. However, the point we make here is that the overall detailed study of mathematics is essential for our rationale, which cannot be done in more general single-authored books. Paul Davies himself [16, p. 16] starts the reader with 'no previous knowledge of mathematics or physics is necessary'. Philip Ball, in his beautiful exposition of pattern formation in nature, likewise, restricts the mathematical treatment – 'I will not need to use in this book' (he says [17, p. 14]) 'any more mathematics than can be expressed in words rather than in abstruse equations'. Despite this restriction, however, Ball eulogizes mathematics – 'the natural language of pattern and form is mathematics … mathematics has its own very profound beauty … mathematics is perfectly able to produce and describe structures of immense complexity and subtlety ' [17, pp. 10–11].

The conclusion is straightforward – mathematics is an essential part of the design 'spectrum'.

Thermodynamics

The second law, like the first, is an expression of the observed behaviour of finite systems
[Gordon Rogers and Yon Mayhew, 18, p. 809]

Thus the second law is a statistical law in statistical mechanics
[Stuart Kauffman, 2, p. 86]

In seeking to understand thermodynamics there is not so much an obstacle to be surmounted, as ditches to be avoided. This is because thermodynamics uses concepts in common English use like 'energy', 'work', 'heat' and 'temperature', and because the First Law is an expression of the well-accepted 'conservation of energy' principle. However, these concepts are very closely defined in thermodynamics, and it is essential to understand their definitions. When we reach the Second Law, the problem is all too clear. What does entropy *really* mean? Why do different statements of the Law look completely different? So an 'amateur' understanding of thermodynamics can lead to an absence of appreciation of the Zeroth Law [to do with equilibrium and temperature] an erroneous confidence in First Law issues, and greater or lesser confusion regarding the Second Law! These are ditches indeed.

The other key aspect of thermodynamics is that it is part of the warp and weft of our industrial society. It was through the French engineer Carnot's brilliant perceptions, leading to the Second Law, the procedures for optimising work-producing heat engine design became clear. The same Law, with its stated necessity for heat rejection and reversibility, was the explanation of what otherwise looked like rather low heat engine efficiencies. In fact, essentially as a consequence of the Second Law, best practice power station efficiencies were of the order of 30% over a long period of time. As a major consequence of the enormous consumption of fossil fuels [coal and oil for example] in those power stations, and including internal combustion engines, carbon dioxide concentration in the atmosphere has increased dramatically. Over the two centuries 1800–2000 the increase has been some 28%, with approximately half that figure occurring since 1960. This is shown by Fig. 3.3 of John Houghton [19, p. 31]. Such is a major part of the background to the Greenhouse effect.

Carnot perceived that a crucial factor in achieving higher efficiencies was for the heating source to be at the *highest possible temperature*, which led in its turn to the definition of the Absolute Temperature Scale by the British engineer, Lord Kelvin.

It was then the German physicist Clausius who defined entropy – 'a new physical quantity as fundamental and universal as energy' [Kondepudi and Prigogine, 20, p. 78]. It was not just the heat that was important, but the *heat modified by the absolute temperature*, the entropy, that was needed. As a consequence, quantitatively low values of entropy are 'good', and perhaps this has led to conceptual difficulties. Similarly, entropy increases are caused by the individual processes in the heat engine operation [irreversibilities]. Finally, the Austrian physicist Boltzmann developed a theory of molecular statistics and entropy, leading to the association of entropy with *disorder* [20, p. xii]. Altogether then non-scientific [and even scientific and engineering] readers might be forgiven for viewing entropy as a sort of 'spanner in the thermodynamic works' – to be kept as low as possible.

Now it is not fully appreciated that the Laws of Thermodynamics are *empirical* – so [write Rogers and Mayhew] 'the Second Law, like the First, is an expression of … observed behaviour'. That empirical prevalence extends to the statistical mechanics interpretation – 'the macro state is a collection of microstates … the Second Law can be reformulated in its famous statistical mechanics incarnation' [Kauffman, 2, p. 86]. Post World War II, Shannon's information theory, has caused entropy to be associated formally with information. 'The conclusion we are led to' [Paul Davies, 21, p. 39] 'is that the universe came stocked with information, or negative entropy, from the word go'. Incidentally, our 'forgiven' readers might feel well justified by the expression negative entropy!

So much for the classical past of thermodynamics. Davies's quote points us to a new look at the subject. *What we are now seeing is an almost overwhelming desire to systematise the application of thermodynamics to biology.*

… vast amounts of entropy can be gained through the gravitational contraction of diffuse gas into stars … we are still living off this store of low entropy [Roger Penrose, 22, p. 417].

… far from equilibrium states can lose their stability and evolve to one of the many states available to the system … we see a probabilistic Nature that generates new organised structure, a Nature that can create life itself [Dilip Kondepudi and Ilya Prigogine, 20, p. 409].

The sequence of the application of thermodynamics to biology can be traced back to Erwin Schrödinger's lectures given at Trinity College, Dublin, Ireland, at the height of the Second World

War, currently published as 'What is Life?' [23a, 23b]. In the chapter 'Order, Disorder and Entropy' Schrödinger postulates the following sequence: that living matter avoids the decay to equilibrium [or maximum entropy] by feeding on negative entropy from the environment, that is by 'continually sucking orderliness from its environment', and that the plants which form the ultimate source of this orderliness, themselves 'have the most powerful supply of negative entropy in the sunlight' [23a, pp. 67–75].

To take things further, we turn from the more readily available Reference 23a, to 23b, where Roger Penrose's original Foreword has evolved into a substantial Introduction. This latter Introduction is an important source in itself as it takes up Schrodinger's postulation of the sun's negentropic effect. Using Penrose's own words, [23b, p. xx]: the Sun is not just an energy source, but … a very hot spot in an otherwise dark sky … the energy comes to us in a low-entropy form … and we return it all in a high entropy form to the cold background sky. Where does this entropy imbalance come from? … the Sun has condensed from a previous uniform distribution of materials by gravitational contraction. We trace this uniformity … to the Big Bang … the extraordinary uniformity of the Big Bang … is ultimately responsible for the entropy imbalance that gives us our Second Law of Thermodynamics and upon which all life depends. So, too, we repeat Davies [21, p. 39]' as 'a kind of converse to chaos theory'.

> *I regard the concept of 'gnergy' as one of the most important results of my theoretical investigations in biology over the past two decades*
>
> [Sungchal Ji, 25, p. 152]

> *Such a law could be my hoped-for fourth law of thermodynamics for open self-constructing systems*
>
> [Stuart Kauffman, 2, p. 84]

We pass rapidly on to Sungchal Ji, with the proposed concept of 'gnergy' encompassing both energy and information, and to Kauffman with his hoped-for Fourth Law of Thermodynamics. At least they cannot be accused of lack of ambition! Ji's rather beautiful graphical interpretation of the evolutions of density and information since the Big Bang [25, p. 156] is reproduced here, as Plate III. [In doing so, however, it may be noticed that Ji's zero initial information density is hardly consistent with Davies' initial stock of information. This point will be addressed in the chapter on thermodynamics in Volume 2 of the Series]. Eric Chaisson's more concise research paper approach [26] should be noted, as it elegantly combines and quantifies some of the key issues raised by both Ji and Kauffman. It forms a nice introduction to the subject area.

We are about to bury our thermodynamics 'bone'. However, it must be appreciated that other 'dogs' still prefer non-thermodynamics 'bones', for example Stephen Boyden [27] and Ken Wilber [28]. The latter's ambitious 'A Theory of Everything' is sub-titled 'An Integral Vision for Business, Politics and Spirituality'. In his Note to the Reader he makes what to him is a conclusive remark about the 'second law of thermodynamics telling us that in the real world disorder always increases. Yet simple observation tells us that in the real world, life creates order everywhere: the universe is winding up, not down' [28, p. x]. For readers who, like me, cannot put their 'bones' down, this statement cannot be allowed to rest, and represents another issue for Thermodynamics in Volume 2. However, my comment is not meant to be pejorative. Ken Wilber seeks, as do so many writing in this subject area, a mastery almost painful to appreciate!

The final point here is the most interesting of all, namely that the origin of life remains a question. 'How this happened we don't know' said Stephen Hawking recently [29, p. 161]. Somewhat differently, Ilya Prigogine some ten years ago [30, p. 24] – 'we are still far from a detailed explanation of the origins of life, notwithstanding we begin to see the type of science which is necessary … mechanisms which lead from the laws of chemistry to "information". However, where there's a bone there's a dog, [if the reader will forgive this final use of the metaphor] and in this case our dog is Michael Conrad. Conrad's essential thesis contrasts with that of Schrödinger [31, p. 178], and is rather that – to quote the Abstract [31, p. 177] – 'the non-linear self-organising dynamics of biological systems are *inherent* [my italics] in any … theory … requirements of both quantum mechanics and general relativity'. Conrad's line [ten of the twenty four references in 31 are by himself as sole author] is termed the fluctuon model, and is particularly interesting in relating to 'nanobiological phenomena and that might be detected through nanobiological techniques'. Stuart Kauffman [2, Chapter 10] similarly surveys quantum mechanics and general relativity, but more in the nature of questioning than Conrad's tighter theorising ….

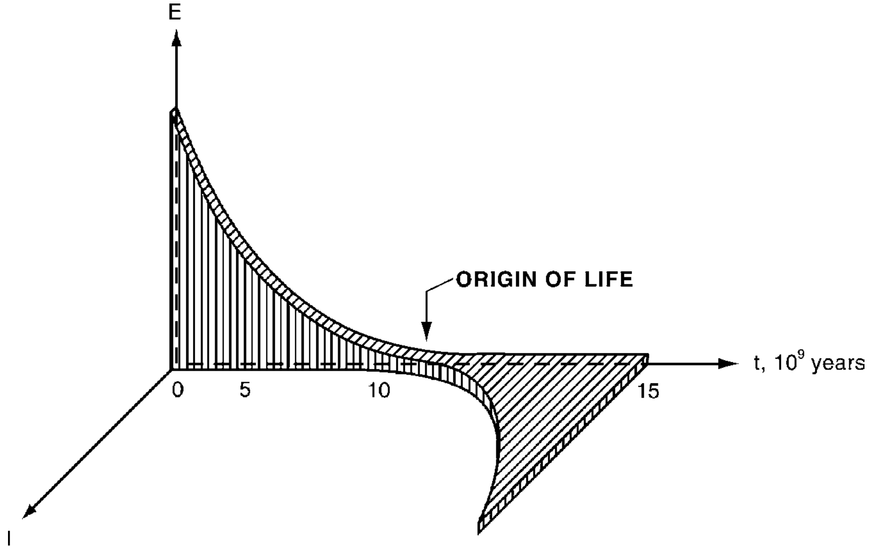


Plate III: The Evolutionary History of the Universe.

In this graph, E and I represent energy and information densities. t is time, on an approximately logarithmic scale, with the origin an estimated 15 billion years ago at the Big Bang. The substantial increase in I occurs following biological 'emergence of the first self-replicating systems … about 3 billion years ago' [after Sungchal Ji].

History

'This concept of an ideal, perfect form behind the messy particulars of reality is one that is generally attributed to Plato'

[Philip Ball, 17, p. 11]

'Leonardo da Vinci was my childhood hero, and he remains one of the few great geniuses of history'

[Michael White, 32, p. xi]

> *'The only scientific book I read that summer was Charles Darwin's 'The Origin of Species' ... but we do still read Darwin'*
>
> [Kenneth Miller, 11, p. 6]

Having sought to show that a fuller understanding of 'Design in Nature' needs to be both mathematically and thermodynamically oriented, we will now point out its historical aspects. We will focus on thee principal characters – Plato, Leonardo da Vinci and Darwin. It is not so easy to give reasons for the choice of these three, but I believe that they represent timeless flashes of genius. Somewhat unexpectedly, they can be viewed in the context of *engineering design*.

So, Plato is associated with one of the key aspects of design, namely form [cf quote by Ball above]. Leonardo epitomizes the ideal of the engineering designer, namely a 'universal man' at home in any branch of knowledge and able to conceptualise almost limitlessly. So we read [33, p. 488] … 'Italian painter, sculptor, architect, engineer and scientist … of immensely inventive and enquiring mind, studying aspects of the natural world from anatomy to aerodynamics'. Finally, Darwin can be associated with the idea of progress and adaptation with time [namely, evolution]. It is difficult to overemphasise this, the point being made explicitly in the *titles* of two recent books. Michael French's [7] title is 'Invention and Evolution'. Design in Nature and Engineering'. Similarly, Norman Crowe on architecture [34] 'Nature and the idea of a man-made world. An Investigation into the Evolutionary Roots of Form and Order in the Built Environment'. These are but two examples. We mentioned flashes of genius. These flashes also possess mathematical connotations. *...Plato esteemed the science of numbers highly* … [David Smith, 35, p. 89].

In that Plato postulated transcendent [non-earthly] form, he must have been close in approach to the multi-dimensional character of the studies we have already discussed in our Prologue. Platonism *per se* is dealt with at some length by Roger Penrose [22, pp. 146–151] whose 'sympathies lie strongly with Platonistic view that mathematics truth is absolute, external and eternal …'. Paul Davies [16, p. 145] carries Penrose's sympathies forward as … 'Many physicists share his Platonic vision of mathematics'.

> *'Norway builds Da Vinci's 500 year-old bridge ... it conformed with the laws of mathematics'*
>
> [Roger Boyes, 36]

Turning to Leonardo, Michael White freely admits his hero's deficiency in this area. And yet, despite Leonardo's being 'barely competent' [32, p. 152] in mathematics and reliant on Pacioli ['he gained a good deal from Pacioli [32, p. 153]], he designed better than he knew. So we have the Norwegian artist Veljorn Sand, who was the persistent catalyst [it took him 5 years] to secure funding for Leonardo's design, paying Leonardo two compliments, firstly to do with his genius ['when you work with geniuses, you work with eternal forms that never go out of fashion'] and secondly his *implicit* mathematical ability [… 'the design was of lasting beauty because it conformed with the laws of mathematics and geometry … the Mona Lisa of bridges']. To round off Leonardo's relationship with mathematics, he was nothing if not ambitious, and is on record himself as having a very deep commitment. Is it a case of an initial shortcoming being more than subsequently compensated for? So Sherwin Nuland [a surgeon] gives this different picture of Leonardo … 'for Leonardo, mathematics was the ultimate key to the understanding of the nature he scrutinised so carefully … to all of science, including the biology of man' [37, p. 53]. Nuland quotes Leonardo as 'no human investigation can be termed true knowledge if it does not proceed to mathematical demonstration'.

Darwin and Mathematics

> *Inside the sanctum sanctorum they got things done ... to Stokes this was 'flimsy to the last degree' ... But Huxley pulled off the coup ... It was published intact'*
>
> [Adrian Desmond, 38, p. 42]

> *'... Kelvin got very few calculations wrong ... here he understandably failed to include the contribution of the heat of radioactivity'*
>
> [Dennis Weaire, 39, p. 61]

> *'Darwin's view of persistent co-evolution remains by and large unconnected with our fundamental physics, even though the evolution of the biosphere is manifestly a physical process. Physicists cannot escape the problem ... We will search for constructive laws true of any biosphere. We will found a general biology. And we will be spellbound'*
>
> [Stuart Kauffman, 2, pp. 245, 269]

Finally, Darwin and mathematics. 'The Origin of Species' [41] is essentially, in engineering terms, and experimental report writ large, unaccompanied by mathematical theory. So we have an amusing account as to why Eric Laithwaite chose physics rather than biology. 'Physics seems to be mostly sums, biology mostly essays … my best friend is going to do biology, so I can keep asking him about it and keep in touch that way. That does it … I'll do physics' [6, pp. xi–xii]. Eric Laithwaite's schoolboy choice was a personal reflection of an extremely sharp division in the Royal Society regarding the application of Darwin's work. In fact, Desmond's quote above relates not to a publication of Darwin himself, but an ms submitted on Huxley's suggestion by Kovaleski. The real point here is that the Royal Society's conservative Physical Secretary, George Gabriel Stokes' [38, p. 41] opposed the Kovaleski acceptance because it would make 'speculative Darwinism as axiomatic as Newton's laws' and compromise the rock-like status of knowledge' [38, p. 42]. Now GGS lost, and if Desmond's comment is fair, GGS was spectacularly wrong since Darwin *is* roughly on a par of acceptance with Newton's laws. Not only so, but GGS's close friend Kelvin managed to miscalculate the age of the Earth [second quote above], a scientific *cause celebre* of the time.

GGS is given 'a bad book' by Desmond. In fact, he was an extraordinarily talented and productive physical mathematician and Stokes Summer Schools are run in Ireland, organised by Alastair Wood of Dublin City University [who wrote the parallel section on GGS [39] to that of Kelvin]. I declare a personal interest here. I have an immense regard and affection for Stokes, having worked for decades on numerical studies of convective heat transfer using the Navier-Stokes equations. In fact, Stokes spoke better than he knew, in making an outright comparison [having renamed the word 'speculative'] of Darwinistic [biology] with Newtonian [Physics]. That 1873 assessment was repeated in out anecdotal comment of Laithwaite around 1940, and repeated more tellingly by Kauffman in 2000. Here we remind ourselves that Kauffman is a biologist himself.

Digressing, Darwin was not the only experimentalist to have problems with the Royal Society. Joule [James Prescott Joule 1818–1889] the near-genius who worked assiduously on the equivalence of various forms of energy – notably heat and work – suffered the indignity of having only abstracts of submitted papers published by the Royal Society, on two occasions [J.G. Crowther, 41, pp. 189, 204]. He was young, very young, so despite the setbacks he was still only 32 years old when finally elected to the RS [41, p. 214].

Our final Darwin-related character is Kelvin who, despite the age-of-the-earth *faux pas*, has almost ethereal status of having proposed the Absolute Temperature Scale. In a subsequent volume in this series it is intended to focus on the contributions of [the two Scotsmen] James Clerk Maxwell and Kelvin to thermodynamics, and how this now relates to present day biology –

information, complexity and the genome for example. The latter is epitomised by the recent work of Jeffrey Wicken, the full title of a major publication speaking for itself – 'Evolution, Thermodynamics and Information. Extending the Darwinian programme' [43]. So do the titles of some 17 Journal publications that he references [43, p. 233] for example 'A thermodynamic theory of evolution' in 1980 [44].

In all this, out quiet participant is Darwin himself. Part of his genius, I believe, was his caution, and he let his data collection speak for itself. No mathematics *there*, but an immense sub-surface, iceberg-like, volume of mathematics *underneath*, shown for its worth, as the genome unfolds, and interpreted in terms of information, complexity and Shannon entropy by those such as Kauffman and Wicken.

History summarised

So our three examples of Plato, Leonardo da Vinci and Darwin, have been given a brief introduction. Rather improbably, their genius has been introduced in terms of *engineering design* and *mathematical significance*. Above all, their genius was, and is, timeless. How else could Plato's views on form and mathematics be regarded as relevant two and a half *millennia* later? How else could Leonardo's bridge design be accepted half a millennium later? How else could Darwin's conclusions stand the test of exhaustive and sometimes hostile assessment, lasting for almost a century and a half?

A further aspect of this timelessness, which will be merely stated rather than discussed, is that the Renaissance [epitomised by Leonardo] had as one of its sources the rediscovery of the Greek texts … 'the finding of ancient manuscripts that gave the intellectuals of the Renaissance direct access to classical thought …' [32, p. 39]. So Michael White gives as Appendix 11: 'Leonardo and his place in the History of Science' [32, pp. 339–342], a chronological sequence running from Pythagoras through to Newton ….

Epilogue

Miraculous harmony at Epidaurus [Henri Stierlin, 45, p. 168]

At the commencement of the Prologue to this Introduction, two 'almost miracles' were described. We conclude with a final example going back to 330 BC – to the absolute end of Greek classicism [45, p. 227]. 'Miraculous harmony at Epidaurus' is how Henri Stierlin describes the wonderfully preserved Greek 'theatre set into the hill of Epidaurus' [44, pp. 168–169] – see Plate IV. There are three distinct aspects to this piece of architecture by Polyclitus the Younger. The design has a mathematical basis - including what is now termed the Golden Section and the Fibonacci sequence. Secondly, the harmony spoken of by Stierlin is a consequence of the theatre's 'symmetry' - a subtle technical quality originating in Greek ideas of form. Lastly, the combination of what we now call 'the built environment' with its natural environment has a timeless aesthetic attractiveness. In fact, Plate IV is reproduced not from the reference we have discussed but a Greek Tourist Organisation advertisment.

In concluding, our introduction has covered an almost impossible range of disciplines, but it is only such a range that can possibly do justice to the theme of design in nature. If 'we' is broadened to comprise editors, contributors and publishers, we want to share our sense of inspiration of design in the natural world and man-made worlds that our three authors of near miracles, Cecil Lewis, Stuart Kauffman and Henri Stierlin have epitomised.

Plate IV: 'Miraculous harmony at Epidaurus'.

(See page xiv of Optimisation Mechanics in Nature): 'Around the orchestra, the shell-like theatre set into the hill fans out like a radial structure, whose concentric rows of seating are all focused on the stage where the dramatic action would unfold. With its diameter of 120m., the theatre of Epidaurus is one of the finest semi-circular buildings of Antiquity. Its design, the work of Polyclitus the Younger, according to Pausanias, dates from the end of the fourth century B.C. It is based on a series of mathematical principles and proportions, such as the Golden Section and the so-called Fibonacci Sequence. Its harmony is thus the result of a symmetria in the real sense of the term' [45, p168].

(Reproduced by permission of the Greek National Tourism Organisation).

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Preface

The structure of DNA gave to the concept of the gene a physical and chemical meaning by which all its properties can be interpreted. Most important, DNA - right there in the physical facts of its structure - is both autocatalytic and heterocatalytic. That is, genes have the dual function, to dictate the construction of more DNA, identical to themselves, and to dictate the construction of proteins very different from themselves.
Max Perutz, Nobel Laureate, quoted by Horace Freeland Judson [1]

...deoxyribonucleic acid turned out to be a substance of elegance, even beauty. Structure and those dual functions are united in DNA with such ingenious parsimony that one smiles with the delight of perceiving it.
Horace Freeland Judson [1]

This, the second of the two volumes providing the 'holistic introduction' to the whole 'Design and Nature' series, focuses initially on DNA as a starting point for the consideration of the evolution of information and complexity in the natural world. The significance of the dual functions of DNA and the complexity of biomolecules, emphatically revealed by the results from the Human Genome Project, are considered both in the context of the way living things work and in relation to the origin of life.

Despite the obvious complexity, DNA function, cellular behaviour in general and the overall life and activities of living organisms all occur within the parameters imposed by the laws of nature that govern the workings of the universe. This is true at all levels of biological complexity from each individual chemical reaction through specific activities of organisms such as walking or flight to the functioning of whole ecosystems. It is equally true of the activities of humankind: we work within the laws of nature, not just as biological organisms but also when we are acting as engineers, inventors or trying to mimic specific aspects of life such as self-replication or autonomy. Further, consideration of particular fields of human endeavour as living systems may help to improve those systems as we analyse the parallels between the activities of human society and the wider world of biology, especially in relation to design and information.

We have thus covered design and information in biology at several different levels and from a number of perspectives. The book is not a comprehensive coverage of the subject - indeed a comprehensive coverage in one book or even in several would be impossible. Rather, as stated in

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the Preface to Volume 1, each chapter is a personal flash of illumination from the author or authors and it is very much hoped that these chapters will indeed illuminate for our readers particular facets of the subject with which they are as yet unfamiliar.

We are very grateful to the authors for so willingly agreeing to contribute to this volume, which, for several of them, is unlike any other book to which they have previously contributed. It is their scholarly and thoughtful writing that has enabled us to achieve the flow from molecules to systems that we envisioned when the volume was conceived. We are also indebted to our friends and colleagues at WIT press who have supported and encouraged us in this work and who have looked after the production process so efficiently.

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