Chapter 6

The laws of thermodynamics and *Homo sapiens* the engineer

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Abstract

One of the key developments in the university scene since the publications of *The Origin of Species* has been the emergence of engineering as a discipline in its own right. Over the same timescale the realization has developed that the laws of thermodynamics, universal in their engineering scope, must also apply to biology and living systems. As a matter of historical fact, the relationship between biology and thermodynamics had a bad start, and the reasons for this are discussed. Now one of the foundation concepts for thermodynamics is that of the heat engine, stemming from the radical achievement of the Industrial Revolution of being able to produce mechanical work from heat. In this chapter, we find that by re-defining the heat engine in terms of output, all organisms can be viewed as ‘survival engines’, certain animal species and man as ‘work engines’, and man himself as a ‘complexity engine’. A number of examples are taken from the process of building the dome of the cathedral at Florence by Brunelleschi, a defining moment in the history of the Renaissance. This interpretation of *Homo sapiens* is consistent with Lumsden and Wilson’s assessment of man as being the only eucultural species: various consequences of this are discussed. The chapter completes our trilogy of studies on the laws of thermodynamics, by then focusing on the possibility of further laws for living organisms, especially Kauffman’s proposal for a fourth law. Finally, a concluding discussion entitled ‘How mathematical is biology?’ highlights the question of including mathematics as part of that integration.

1 Introduction

1.1 General

This chapter completes our trilogy of studies addressing the relationship of thermodynamics with biology. In Chapter 5, our direct personal contributions were limited to topics from physics

and engineering. We now seek to apply the practices of *engineering* thermodynamics to living systems in general, focusing on the key concept of the *heat engine*. We will see that it is a quite straightforward approach, verging on simplicity.

Now a perceptive reader might well ask why this has not been attempted before. It possibly stems from two historical reasons: the originally almost non-existent status of engineering in UK universities and the initially bad relationship between biologists and energy specialists.

The ethos of the current volume and series rests on the ‘parallel between human design and nature’. The former is self-evidently largely an engineering activity. Today engineering, including even the various branches of engineering, is a highly regarded university discipline in its own right. Because this was not always so, the idea that biology and engineering could have an advantageous dialogue was largely absent.

Much the same could be said of thermodynamics. In Kondepudi and Prigogine’s historical introduction to the second law of thermodynamics, pride of place is given to James Watt, who ‘obtained a patent for his modifications of Thomas Newcomen’s steam engine in the year 1769’, ([1], p. 67). Now in a popular encyclopaedia [2] Watt is explicitly described as a ‘Scottish engineer’. Little did the Victorians of Darwin’s day deem that thermodynamics had anything useful to say about biology.

With the benefit of hindsight, however, the signs were already there, with Clausius’ famous summary of ‘the two laws of thermodynamics ...

The energy of the universe is constant.

The entropy of the universe approaches a maximum’ ([1], p. 84).

If thermodynamics could cope with the universe, why not with the biological material generated in the universe?

1.2 The heat engine

Now one of the key concepts of engineering thermodynamics is that of the *heat engine*, an ‘engine that performs mechanical work through the flow of heat’ ([1], p. 69), and this was what Sadi Carnot studied in developing the origins of the second law. This is paralleled by the latest developments in second law interpretation originated by Prigogine and based on non-equilibrium thermodynamics. This allows ‘a non-equilibrium system to evolve to an ordered state as a result of fluctuations’ ([1], p. 426), arising from the dissipation of free energy. Such are called *dissipative structures*.

The above brief discussion epitomises Kondepudi and Prigogine’s approach to the extent that the subtitle of [1] is ‘From Heat Engines to Dissipative Structures’. Also, at a conference in 1986 in Piscataway, USA, Prigogine [3] discussed Schrödinger’s *What is Life?* study of 1943 [4] – which he termed ‘Schrödinger’s beautiful book’. One of the focuses is that ‘living matter escapes approach to equilibrium’, and Prigogine notes that it was one of the sources for his own interest in non-equilibrium processes.

Now in the same conference volume as [3], Sungchal Ji [5] gives an exhaustive exposition of what he terms ‘biocybernetics’. He treats a number of living systems, in the broadest sense of the word, as machines. These include the human body (called the Piscatawaytor) and human society (the Newbrunswickator). Such terms are an extrapolation, incidentally, of the original model in dissipative structure studies, the Brusselator (after its place of origin, the Brussels School of Thermodynamics [1], p. 439).

One of Ji’s biological machines is the living cell, the model ([5], p. 80) being named the Bhopalator, from another conference at Bhopal, India, in 1983. A crucial component of this machine analogue of the cell is ‘Dissipative Structures of Prigogine’.

We end this introduction by noting that Ji concentrates on the *internal* workings of his biological machines, whether, for example, they are living cells, the human body, or even human society. However, if instead we view such living systems as ‘Black Boxes’, then perhaps they can be interpreted as adapted versions of Heat Engines. In so doing we will be able to combine the earliest and the latest studies of the second law of thermodynamics.

2 Biology and thermodynamics: a bad start to the relationship

... now he lashed the techno – flunkies from the temple – the ‘Engineers ...’

Adrian Desmond [6], p. 249

He deserves to be called a mathematician, as well as a physicist and even an engineer.

Denis Weaire [7], p. 57

I.K. BRUNEL ENGINEER 1859 (Monumental lettering on the Royal Albert Bridge)

R.C. Riley [8], p. 8

A bad relationship developed between biology and thermodynamics, following the publication of *The Origin of Species* (henceforth ‘Origin’). It was intimately connected with the status of engineering and it focused on two main characters, T.H. Huxley and William Thomson (Lord Kelvin).

Firstly, we consider the status of engineering in the UK in the days of Darwin and T.H. Huxley. As far as universities went, it was poor. Whereas the former was happy to consult the Cambridge *mathematician* ‘Professor Miller ... this geometer’ [9] on the structure of the honeycomb, Huxley saw *engineering* as a contamination of the purity of science. Desmond expresses Huxley’s fear that the public veneration of science would switch to its products, ‘its *engines* and telegraphs’ ([6], p. 250). However, Huxley’s attitude was ambivalent. ‘Sir Joseph Whitworth put £100,000 into the DSA’s science scholarships and joined the steel magnate Sir William Armstrong to fill Huxley’s purse’ writes Desmond ([6], p. 252). These were the same Sir Joseph Whitworth and Sir William Armstrong who were presidents of the Institution of Mechanical Engineers (IMechE) in 1856/57 and 1861/62, respectively; the IMechE as a learned society having been founded some 10 years earlier in 1847 [10]. Their engineering identities were similarly reflected at the Institution of Civil Engineers (ICE) – already 40 years old at the ‘Origin’s publication (1818 [10]). There Sir Joseph Whitworth served as Member of Council 1855/64 and 1870/87, with Sir William Armstrong again as president in 1881/82 [10]. Finally, the epitome of Victorian engineering, I.K. Brunel (similarly with the ICE as vice-president 1850–1859) in the very year of the ‘Origin’, completed his masterpiece railway bridge over the river Tamar. He wanted the world to know *he* was an engineer, so he told them so on his bridge. Huxley, at the same time as he was attacking the engineers ‘would enjoy a wing in Whitworth’s Matlock mansion’, and ‘annual holidays at Armstrong’s Gothic manor’ ([6], p. 252).

Furthermore, university engineering was not actually non-existent. Specifically, it was at Glasgow that 1840 saw the first British chair in ‘civil engineering and mechanics’ with the appointment of Lewis Gordon ([11], p. 35). We have already mentioned James Watt who became a ‘Glasgow-legend’ ([11], p. 34). Even as a civil engineer, however, Lewis Gordon’s turbine water-wheel studies used a ‘criterion for maximum economy’ ([11], p. 35), derived from Lazare Carnot, the father of the second law originator, Sadi. A pattern was emerging – at Glasgow the

pioneering of engineering was intimately associated with Watt and thermodynamics. Gordon was followed in the engineering chair by Rankine – the thermodynamics specialist whose cycle is mentioned in [12] (p. 214). In turn, Rankine was succeeded by James Thomson in 1873 ([7], p. 57; [11], p. 104) – the brother of William Thomson, Lord Kelvin, our second principal character. Although Kelvin was appointed to the ‘natural philosophy’ chair at Glasgow in 1846 he embodied both thermodynamics and engineering. Even in his ‘inaugural Latin dissertation’ the earth’s cooling was a focus ([11], p. 25), and Crosbie Smith describes his coming as ‘a quest for engineering credibility’ ([11], p. 4).

Kelvin was an immense figure in Victorian science, described by Bill Bryson as a ‘kind of Victorian superman’ ([13], p. 68) – or by Denis Weaire as ‘mathematician ... physicist and even an engineer’. He was anchored at Glasgow, declining offers to occupy the Cavendish chair at Cambridge ([7], p. 57). An exhaustive 800-page biography is also provided by Crosbie Smith, with Norton Wise [14]. So the stage was set for a scientific row of the grandest proportions when Darwin published a calculated age for the earth of over 300 million years in his first edition (removed in the 3rd edition due to the controversy ([13], p. 67)). At first, this difference was not too bad – 100 million years from Kelvin [15] (p. 370). Unfortunately, Kelvin kept revising his figures *downwards* ultimately, in 1897, ‘to a mere 24 million years’ ([13], p. 69). The argument was crucial for Darwin and Huxley, and the latter ‘in his role of defence counsel’ ([15], p. 370) was right on this issue. The problem was the lack of the effect of radioactive heating (then unknown) in Kelvin’s model.

It is difficult for us to overestimate the effect that Kelvin’s lack of success must have had on long-term biological/thermodynamics attitudes and relations. After all, in a crucial thermal subject area, the ‘amateurs’ proved to be right and the ‘superman’ wrong.

Looking at the broader issue of the assessment of Kelvin as an *engineer*, is a rather disappointing process. J.G. Crowther, while noting Kelvin’s ‘seventy engineering patents’ and his ‘theoretical and practical engineering ability’ insists this was at the expense of his not achieving highest scientific success. Had he ‘concentrated ... on a few fundamental problems he might have become ... the second Newton’ ([16], p. 236). With the notable exception of [11], these days Kelvin is claimed essentially to be a physicist [17, 18].

Time does not permit us to discuss the wider issues of Crosbie Smith’s convincing core thesis of the underlying battle between the scientific naturalism of the X-club centred in London, and the ‘North British scientists of energy’ ([11], p. 7 and 171). While ‘Darwin’s evolutionary theory’ was the chief weapon, John Tyndall, a fellow-member with Huxley of the X-club, also introduced ‘energy conservation’. ‘... he unleashed a massive extension of hostilities’ ([11], p. 171). It focused on Tyndall’s promulgation of the merits of Mayer ‘the German physician’ as opposed to those of Joule ‘the English natural philosopher’ ([11], p. 9) in the field of energy. In this equally strategic, but much less well-known dispute, it was the ‘scientists of energy’ who succeeded and the X-club who lost out.

It was no wonder, then, that biology and thermodynamics could not engage constructively at first.

3 The heat engine and the work engine

3.1 The heat engine re-visited

The idea of stressing the engineering focuses of thermodynamics is almost a tautology. However, we now repeat this, together with the point made in [8], that ‘a careful progression of precise

Figure 1: Heat engine diagram.

definitions' is crucial. We have already given Prigogine's definition of a heat engine. This could be extended to: 'a heat engine is a system operating continuously over a cycle, exchanging heat with thermal reservoirs and producing work'. This is shown in Fig. 1 (figure 8 of [12]), where the number of reservoirs is the conventional two. (Also, a direct heat engine is shown, but reversed heat engines for refrigerators and heat pumps are also possible – figure 9 of [12]).

We now propose a unified treatment of biological organisms as thermodynamic engines.

We will re-define the 'heat engine' in terms of *output* and identify three alternative modes:

- (i) survival engine, relating to all species, including man (engineering equivalent, an idling heat engine);
- (ii) work engine, relating to draught animals and man (engineering equivalent, a heat engine proper);
- (iii) complexity (or information) engine, relating to man only (engineering equivalent, designing, computing, etc.).

We will examine to what extent the biological and engineering aspects are self-consistent, and whether the complexity engine concept can shed light on the entropy/information equivalence.

Finally, the focus on the *output* of such engines, allows the inclusion of pre-Industrial Revolution engineering in its scope. In fact, Brunelleschi's building of the dome of the cathedral at Florence will provide the majority of the examples used in this study. Information is derived from the recent publications of Ross King [19] and Paolo Galluzzi [20].

3.2 Internal combustion and the work engine

Although the heat engine is a core thermodynamic concept, it is not readily applicable to many real situations. In particular, internal combustion is an 'open system' or 'control volume' into which flow fuel and air, and out of which flow combustion products. As shown in Fig. 2 it may still be regarded as a black box. In practice, in thermodynamic analysis, it is conceptually replaced by an *external combustion* engine, with air as a working fluid. When, in addition the processes within the cylinder are re-defined by approximate reversible non-flow processes, a complete cycle is defined, and may be completely analysed thermodynamically. Such cycles are termed air standard cycles, and their efficiencies, air standard efficiencies.

In the case of spark-ignition engines, locomotion from which we will compare with that from the horse, the air standard cycle is called an Otto cycle.

Figure 2: Diagram of internal combustion engine (after [9]).

Figure 3: The heat engine and the work engine.

Figure 4: Locomotion by internal combustion and the horse.

Figure 3 shows how the heat engine may be replaced in terms of *output* from an *open system* by what we term a *work engine*. The latter is defined with as much thermodynamic flexibility as possible.

In the case of the spark-ignition internal combustion engine, the black box E represents an air standard Otto cycle device. For the work engine, the new black box WE represents an authentic internal combustion cylinder–valve–piston arrangement. There is still a heat rejection from WE to the environment, as it operates at a temperature well above ambient.

3.3 Locomotion by car and horse

We may now compare locomotion by mechanical and biological means, as in Fig. 4.

The equivalence is extremely close, the fuel and products of the internal combustion engine being replaced by food and waste in the case of the horse. For multiple passengers, in both cases

an additional tool T is required – either the car proper or a carriage. Also, for each arrangement, a form of intelligent control by man is needed.

In the history of thermodynamics, this logic was used in reverse, to such an extent that the horse power was used as an unit of performance. James Watts is credited with its introduction ([11], p. 198), 1 horse power being 550 ft · lb (force) of work per second in the old British Imperial system of units, or 746 watts.

3.4 Other draught animals: the ox

While the above comparison is rather precise in the case of horse-drawn locomotion, the work engine concept also applies to any draught animal including elephant, camel or even man himself. In particular, in agriculture there was an ongoing competitive use of horse or ox in Europe over the large time span of 1100–1800 AD. While in Britain the number of horses increased in agricultural and draught work over this period, in southern Europe the donkey and mule were preferred to the horse – the ox being common to both ([21], pp. 154/155).

4 The survival engine: e.g. the lizard

Thermodynamically speaking (and not considering the food chain), most species do not produce work: they just survive. Hence they, as survival engines, approximate to the idling heat engine which consumes fuel, which is ultimately entirely lost as a heat rejection. Such an engine, of course, has zero work output.

We take as an example an *ectotherm*. This animal has, as an integral part of its metabolism, an external source of heat, which, in the case of the lizard means solar radiation. Figure 5 demonstrates the thermal regulation that the lizard has to undertake over the daytime period.

Figure 5: Thermal regulation of an *ectotherm* (after [22]).

Figure 6: An engine with no work output: mechanical and biological.

As an *ectotherm*, the lizard exemplifies an even closer comparison with the idling heat engine, as solar heating (i.e. using a hot source reservoir) is an integral part of its metabolism. Figure 6 compares the two.

5 Work engines and the dome of the Florence Cathedral

5.1 The dome

The building of the dome of the cathedral at Florence in Italy was a massive undertaking, and a defining moment in the history of the Renaissance. It took 16 years to build, from 1420–1436 ([10], p. 141). The name of the architect and builder, Filippo Brunelleschi, is synonymous with that of the dome, and it seems incredible that previously he was ‘a goldsmith and clockmaker’ (p. 11). The achievement was indeed impressive. The base and top of the dome were around 54.5 and 87.5 m above ground level, the lantern adding a further 22 m. Its weight has been estimated at 37,000 metric tons, with probably more than 4,000,000 bricks used. The key design feature is that it is the largest dome ever built without having to use wooden centring.

5.2 The rota magna or treadmill

From Roman times, the device used for major work output of the kind envisaged in lifting the materials for the dome was the *rota magna* or treadmill, described in detail in [23] (pp. 11–13). Presumably, the Romans would have used slave power. In fact, the *rota magna* had been used for the construction of the cathedral proper.

Our work engine definition accommodates the *rota magna*, as shown in Fig. 7. The work engine itself comprises *Homo sapiens*, the tool being the treadmill/*rota magna* mechanism.

5.3 Brunelleschi’s ox-hoist

As part of the competition for the building of the dome, the Opera del Duomo (the office of works in charge of the cathedral [19], p. 1) had included a call for plans for a lifting device that could replace the *rota magna*. None were forthcoming (p. 59). Having been appointed as one of the three *capomaestri* (architects-in-chief) (pp. 6/59), Brunelleschi almost immediately started designing what was to prove a completely successful ox-powered hoist. His sheer genius was displayed, not just in the size and power output, but especially in the hoist’s reversible three-speed gearing

Figure 7: The rota magna.

Figure 8: The ox-hoist.

‘for which there is no known precedent in the history of engineering’ (p. 62). Others followed his example. Taccola (Mariana di Iacopo) designed a single-speed horse-powered version ([19], p. 61; [20], figure I.2B.1b). Also, Leonardo da Vinci analysed the whole ‘motor’ in detail, from which a working model has been constructed ([20], figure I.2B.1a).

It seems unbelievable that such a revolutionary engineering design was conceived (using Brunelleschi’s words) as a relaxation – ‘relief ... at night ... in my mind ... from bitter worries and sad thoughts’ ([19], p. 58).

Figure 8 shows the ox-hoist as a diagram, the work engine being the ox or horse, and the tool the ox-hoist mechanism. From Ross King’s quoted figures ([19], p. 63), one ox achieved a work output – including all the mechanical losses in the hoist itself – of about 15,500 ft · lb force/minute. This compared with the notional Horse Power unit introduced by Watt, of 33,000 ft · lb-force/minute.

5.4 Brunelleschi’s revolving crane or castello

Brunelleschi also designed a revolving crane, probably used to position accurately the final stone blocks and to build the lantern. This was an impressive mechanism, at least 20 m high, and it must have dominated the Florence ‘skyline’ of the dome when it was erected at the apex.

This was powered by *Homo sapiens*. Four teams were needed. The first rotated the vertical shaft, which had a complete angular flexibility of 360°. Two more teams worked the screws for radial positioning of both the load and the counterweight which was needed. The fourth team operated the vertical screw. Again Leonardo da Vinci sketched the mechanism in detail, and again a working model has been constructed ([20], figure I.2B.2a).

Figure 9: The revolving crane.

Figure 9 gives the thermodynamic diagram, with the four teams as the work engine and the castello mechanism as the tool.

6 Brunelleschi, the complexity engine

6.1 The ox-hoist

The new hoist was conceptually designed and built over a comparatively short period. The information content of an engineering design has been postulated as the entire specification necessary for manufacture. Considering complexity, it should also include, arguably, the performance of the designed object, such as degrees of freedom. For our purposes, it is not essential to quantify complexity, except to note it *must* include Shannon information.

Over this period of time, then, Brunelleschi had – as a biological/*Homo sapiens* ‘black box’ – a thermodynamic input of food and oxygen. His brain, as a sort of computer hardware analogue, we could assume conservatively was in a similar state at the end – when the hoist was made – as at the beginning (although his skill had gone up). As information (complexity) input, there would have been the rota magna design and the hoist requirements – what we would term a ‘design specification’. As information (complexity) output, there was the entire design and manufacture of the hoist.

So, in this case, Brunelleschi – the *Homo sapiens* – acted neither as a work engine nor a survival engine, but rather as a complexity engine. He converted the (Gibbs) free energy in the food into the increase in complexity represented by the ox-hoist design. Figure 10 gives the appropriate postulated engine diagram.

Exactly the same logic may be used for the castello design.

6.2 The dome

The design and construction of the dome is universally recognised as a masterpiece of engineering and architectural genius. It was largely due to having two shells, a photograph of the intervening air gap, staircase and special brick arrangement being shown as a colour plate in [19]. To use Ross King’s words ([19], p. 167), ‘Today, as for the past five centuries, the mountainous form of the cupola dominates Florence ... The fact that it was built by men – and built amid war and intrigue, with only a limited understanding of the forces of nature – only makes it more of a wonder.’

Figure 10: Complexity engine diagram (few years timescale) for Brunelleschi – designer of ox-hoist.

Figure 11: Complexity engine diagram (lifetime) for Brunelleschi – designer and builder of the dome.

6.3 The dome was Brunelleschi's overall achievement

Together with the mechanical devices, it has a huge information (complexity) content, which in principle could be quantified. For a complexity balance on Brunelleschi's lifetime (and ignoring input from his assistants and workforce) we must include both:

- The genetic complexity content of his brain
- The complexity content of his training/education

Apart from that, Brunelleschi, like all other *Homo sapiens*, had essentially food and air as input. As with the hoist and castello, Brunelleschi the engineer, as a far-from-equilibrium organism, converted the (Gibbs) free energy into complexity. He was a supreme complexity engine. Finally, financial resources are implied – Brunelleschi's food was found for him. Figure 11 shows the corresponding lifetime engine diagram, appropriate to the entire enterprise.

7 Some consequences for *Homo sapiens*

7.1 Man the engineer

In the preceding section, we have shown, essentially at the undergraduate level, how a re-defined thermodynamic heat engine can be applied to living organisms. The free energy/heat rejection

model is based on the original Schrödinger *What is Life?* study as re-interpreted by Prigogine [3]. *Homo sapiens* emerges as a complexity engine par excellence. This is not to deny a complexity engine interpretation of the outputs, say of spiders, of beavers and of the tool-making activities of various species. However, in engineering terms there seems to be no contest, reflecting the one eucultural group of Lumsden and Wilson [24], illustrated by Goonatilake [25] (figure 4.3).

The above, of course, is a reflection of the complexity of *Homo sapiens*. Despite the scientific language of the following quotes, they read almost like poetry.

By far the most complex systems that we have are our own bodies.

Stephen Hawking [26], p. 161

The human body is the most complex material system known to us. It consists of 10^{12} – 10^{14} cells that are organized in space and time (i.e., different parts of the body have different cells and cells at a given site in the body change their properties with time).

Sungchal Ji [5], p. 141

More than one hundred trillion (10^{14}) cells make up an adult human. As a fertilized human egg – a single cell – develops into a university student, its nucleus gives rise to over one hundred trillion nuclei, each containing basically, the same genetic information as did the fertilized egg.

Purves *et al.* [22], p. 191

To build the most basic yeast cell ... you would have to miniaturize about the same number of components as are found in a Boeing 777 jetliner and fit them into a sphere just 5 microns across ... but yeast cells are as nothing compared with human cells.

Bill Bryson [13], pp. 329/330

Also, this interpretation is consistent with Chaisson's work [27], already discussed in Chapter 5 in some detail. His table 1, we are reminded, gives computed free energy rate densities (in ergs/cm³) for, in particular, brains (human crania) and society (modern culture), together with the developmental timescale. '*Homo sapiens* the engineer' is an expression of the progress from brains to society, with Brunelleschi a notable instance over a very short timescale.

This consideration of complexity output, then, consistent with the complex structure of *Homo sapiens*, tends to stress the *distinctive nature* of our species. Even given this distinctiveness Brunelleschi demonstrated himself to be an outstanding example of 'Man the engineer'. His epitaph uses the medieval Latin expression 'INGENII' related to the building of machines. 'It refers to him, therefore, not directly as an architect but as a man of mechanical genius, alluding to the machines he invented in order to raise the dome' ([19], p. 156).

The above distinction of *Homo sapiens* is possibly related to Sungchal Ji's studies [5]. Whereas our focus is on the processes *external* to the human body as an open system, in his 'biocybernetics' Ji studies the *internal* aspects. His Piscatawaytor, redrawn as Fig. 12, demonstrates how complementary the two approaches are.

Ji concludes that '*voluntary bodily motions*, including thought processes' are 'at the centre of our biological being'. He then poses two questions – Is it possible that there is some deep philosophical significance to this conclusion? Have we underestimated the fundamental biological and evolutionary significance of our voluntary bodily motions?

Figure 12: Ji's biocybernetic model of the human body – the Piscatawaytor.

The trillions of cells constituting our body can be divided roughly into 5 groups: the nervous (N), circulatory (C), endocrine (E), immune (I) and voluntary muscular (M) systems. The N, C, E and I systems are thought to act as control systems that cooperate to enable the human body to carry out voluntary motions, M, both macroscopic (i.e. bodily movements) and microscopic (i.e. thought processes).

Sungchal Ji [5], p. 144

7.2 Should there be a biological/engineering synthesis? The case of locomotion

The complexity outputs of species other than man have already been noted. Studies of such are regarded as biology. Consistently, since man is also a biological being, his engineering achievements could also, then, be regarded as biological achievement. This is especially telling in the case of *locomotion*. Bill Bryson, in his usual graphic manner, points out that man is inherently poor at adaptation – ‘pretty amazingly useless’ ([13], p. 217). Focusing on flight, the best we do is jump some few metres above the ground surface! And yet, with the invention of powered flight (let alone space exploration) hundreds of men and women can at one go outfly all other species.

So in the context of flight man is simultaneously very inadaptably and highly adaptable. The reasons for this mismatch must have a thermodynamic background, for the calorific value of typical foods and typical fuels are of the same order of magnitude [28]. As may be inferred from Table 2 of Chapter 5 on page 140, the cell energy processes are complex. There are a number of reasons for this ([22], pp. 125/126). Firstly, molecules are produced ‘that have other roles in the cell’, and secondly the total energy release is split by ‘a series of reactions, each releasing a small manageable amount of energy’. As a consequence, the organism temperature is not too high above ambient, which means the ‘heat rejection’ is correspondingly reduced. Thermal regulation is very precise.

However, second law considerations require a heat engine to operate at a temperature as high as possible for maximum efficiency, and this means the thermodynamic efficiency of *Homo sapiens* is very low. In contrast, powered flight requires as high an energy *density* as possible – kilowatts per cubic metre (or size considerations) and kilowatts per kilogram (or weight considerations)

([12], p. 249) – and uses internal combustion at high temperatures. The levels of calorific value (either fuels or food) both permit powered flight on the one hand, and minimise the bulk of food intake (and the fraction of *Homo sapiens*' time necessary for eating) on the other.

Strictly, it could be argued that there is not a mismatch. The adaptability of *Homo sapiens*, such as it is, is good, almost instantaneous, on what could be described as the microscale. Noting in passing that they were preceded by the 'purely' biological, equine-based locomotion, invented forms of land-, water- and air-based locomotion give man a very good adaptability on, say, the macroscale. In our overall interpretation of *Homo sapiens*, the point of this discussion is to suggest that the two could be *synthesised*. It is allied to the questions posed above by Ji.

7.3 Is *Homo sapiens* just a machine?

This chapter essentially addresses the thermodynamic aspects of living systems in general and *Homo sapiens* in particular. Immediately above we have studied the concept of man as a complexity engine and noted that our concept is complementary to Ji's rationale of various internal biocybernetics models. The reader might well ask whether on these grounds we should regard *Homo sapiens* as *just* a machine, whether thermodynamic or biocybernetic.

The mainstream thermodynamic sequence may be summarised as follows. Kondepudi and Prigogine present two key concepts ([1], p. 427), 'order through fluctuations' and 'dissipative structures'. The first is a general chaotic phenomenon, where random fluctuations cause the system to evolve to one of a number of possible states, which in general is not predictable. In such non-equilibrium systems, chemical reactions/diffusion/concentration patterns are due to dissipative processes. Both are an expression of the consumption of free energy as input to the system. (We have used in the above a number of the specific expressions in [1] (p. 427).) In the model of the cell known as the Bhopalator ([5], p. 80), Intracellular Dissipative Structures (IDSs) as proposed by Prigogine figure prominently. Ji ([5], pp. 71/72) discusses space-dependent and time-dependent IDSs, leading to a 'bifurcation tree for cell metabolism', consistent with the above chaos description. Further, the application of this to variations in calcium concentration in the cytoskeleton is completely consistent with the model Webster and Goodwin use [29] (p. 200) in explaining the morphogenesis of the cap of *Acetabularia*.

However, it is the thermodynamic light that this throws on the sociobiological debate that is of interest here. Ji focuses on the implications of these 'deterministically chaotic' attributes of the Piscatawaytor, agreeing both with E.O. Wilson's stress on the crucial genetic role in social behaviour [30] and with Wilson's *opponents* who introduce the necessity of cultural influences ([31], p. 148). Ji optimistically believes that the model can 'begin to unite such ... opinions into a harmonious and synthetic view of humankind'. He points out that the great sensitivity of chaotic processes to the input boundary condition decouples the predictability so that development can be controlled mainly by cultural influences, '*largely unaffected by individual genetic differences*'. Further, the *control* aspects of the Piscatawaytor (figure 21) suggest to Ji, that 'individuals can exhibit ... egotism, altruism, sex drive, hate, love etc. irrespective of educational or cultural background'.

Wicken concludes *his* thermodynamic study ([32], p. 244) under the subheading 'Chance, Necessity and Freedom'. Like Ji, he has a focus on control. After confessing his ignorance of a number of issues such as 'sense, perception and subjectivity', he asserts 'I do know that *decisions* are operative ingredients in biological nature'. As with Ji, E.O. Wilson appears in the discussion. Wicken contrasts Wilson's confidence in a complete scientific explanation (with reference to a quote from Job in the Old Testament) [31], with his own attitude. 'Wilson feels that science has affirmatively answered this challenge. I do not.' Again reflecting Ji 'The genes – first motif misrepresents the rationale of evolution for many *scientific* reasons discussed over this book'.

Goonatilake [25] also addresses the gene–culture issue in his study of thermodynamics/information. So, on p. 42 and following: ‘there are two types of information ... in cultural animals ... the genetic line and ... the cultural line which is non-genetic ... there are mutual influences between the two ...’. Goonatilake does not see conflict with E.O. Wilson, whose work is extensively discussed in pp. 25–31.

Finally, there are the rather more discursive publications of Ridley [33] and Tiezzi [34]. Ridley’s is a gene–focused book considering only the nature/nurture issue. Thermodynamics and entropy do not figure. Culture, however, is addressed and Ridley confirms our conclusion about the distinctiveness of *Homo sapiens*. ‘The cultural gap between a human being and even the brightest ape or dolphin is a gulf’ (p. 209). He concludes that gene adaptation – ‘genes that allow culture’ (p. 228) – occurred for culture to be initiated. E.O. Wilson appears again (pp. 236, 241–246) and is assessed fairly comprehensively. Ridley is a reconciler – ‘Nature versus nurture is dead. Long live nature via nurture’ is his overall conclusion (p. 280).

Tiezzi on the other hand, is wedded to thermodynamics, embracing Prigoginism. Entropy is essential – ‘a modern scientific culture cannot do without entropy and Darwin’s theory of evolution. Besides entropy and evolution have much in common’ (pp. 36/37). Again we have a discussion of Wilson – Wilson seems to be *de rigueur* – with a stress on his and other sociobiologists’ reductionism (p. 53). Tiezzi is explicitly a non-reductionist – ‘man, unlike animals, has a socio-cultural history’, the future needing ‘scientific humanism and ecological culture ... the only hypothesis suitable for the species *Homo sapiens*’ (p. 163).

So, by introducing thermodynamics, we seem to be consistently led to a conclusion that man is *not* just a machine. In addition, we feel the method is even more important than the conclusion – thermodynamics and entropy must always be on the guest list for any scientific banquet.

8 Is there a fourth law of thermodynamics?

8.1 Kauffman’s statement

... a First Law of ecosystem dynamics, analogous to the First Law of Thermodynamics .... The competition among alternative patterns of energy flow for resources (natural selection) is a Second Law of ecosystem dynamics.

Jeffrey Wicken [32], p. 141

... my hoped-for fourth law of thermodynamics for open self-constructing systems.

Stuart Kauffman [35], p. 84

In this chapter, we have applied formal engineering thermodynamics to living systems. Particularly in the case of locomotion, the definition of ‘work engine’ allows animal-based and mechanical machines to be treated in the same way. Others have taken this logic further to affect the laws of thermodynamics themselves. At one end of the debate is the generalisation of the second law of thermodynamics into ‘the natural law of history’, Brooks and Wiley [36] (p. 356). At the other end is the idea of *additional* laws. So we have Wicken’s two laws of ecosystem dynamics, notably for *natural selection* itself. Also, we have Kauffman’s four ‘candidate laws for the co-construction of a biosphere’ ([35], p. 161). These latter laws, for the evolution of ‘co-evolutionarily constructible communities of molecular autonomous agents’ (p. 162) overlap the area of the laws postulated by Wicken above. Wicken’s statement may be compared with, say, Kauffman’s figure 8.12 ([35], p. 191).

However, it is Candidate Law 4 that Kauffman generalizes into a fourth law of thermodynamics. This former is stated as ([35], p. 160):

Autonomous agents will evolve such that causally local communities are on a generalized 'subcritical–supracritical boundary' exhibiting a generalized self-organized critical average for the sustained expansion of the adjacent possible of the effective phase space of the community.

This statement becomes a postulated fourth law for the biosphere, which Kauffman summarises as (p. 207):

We enter the adjacent possible, hence expand the workspace of our biosphere, on average, as fast as we can.

The context of Kauffman's statement is his other candidate laws. These address the biological hierarchy of organisms–to–species–to–community, and in so doing are comparable to the areas of interest of Wicken and of Brooks and Wiley. The respective quotes below make this comparison explicit.

All autocatalytic organizations – from organisms to ecosystems to socio-economic systems – have two referents: the survival and propagation of certain organizational types, and the provision of the biosphere with patterns of entropy production.

Jeffrey Wicken [32], p. 144

Ecological associations and communities represent higher levels of biological organization above that of species.

Daniel Brooks and E.O. Wiley [36], p. 312

A coassembling community of agents ... will assemble to a self-organized critical state with some maximum number of species per community ...

Stuart Kauffman [35], Law 2, p. 160

In brief then, and in bridging the gap from organisms to biosphere, we see a desire for new biologically – oriented statements arising from the thermodynamic foundations – four candidate laws of Kauffman, two analogous laws of Wicken, and a single generalised version of the second law of thermodynamics, of Brooks and Wiley.

8.2 Discussion

We now consider a number of issues raised by Kauffman. Firstly, coincident with his overall concept is the importance of the direction of time. 'Some fourth law of thermodynamics? An arrow of time?' ([35], p. 151). Although Kauffman claims this is in 'sharp contrast to the familiar idea' (p. 151 and p. 48), his ideas are quite consistent with those of the authors reviewed in the relevant section in Chapter 5. Secondly, his emphasis on the 'adjacent possible of the effective phase space', is parallel to the expanding phase space rationale of Brooks and Wiley. Thirdly, and more subtly, Kauffman views the biosphere as an open system (e.g. pp. 2, 3). This is contra-Wicken, who specifically defines it to *include* all material transport. From choice, it is much easier to use a closed system, but there is a still more significant issue. This is Wicken's degree of closure concept. 'As open systems, organisms fulfil their thermodynamic destinies by

fitting into higher-order systems that express greater degrees of closure' ([32], p. 146). In other words, in parallel with the ascent up the biological hierarchy is a matching increase in the thermodynamic closure. As far as we know, the possible biological significance of this has not yet been addressed.

Finally, Kauffman expresses what may be described as a thermodynamic imperative. It is not just that the 'workspace of the biosphere expands' it does it 'on average, *as fast as it can*' (p. 209), or 'we ... expand the workspace ... on the average, *as fast as we can*' (p. 207), or subject to selection constraints 'a biosphere expands ... about *as fast as it can get away with*' (p. 155). This is caused thermodynamically. '... sunlight shining on our globe, plus some fussing around by lots of critters, has *persistently exploded the molecular diversity of the biosphere into its chemically adjacent possible*' (p. 47). 'Persistence' is a theme word of Kauffman's – we find it on pp. 48, 82, 93, 143, 151, for example. All this adds up to what could be described as a *driven* biosphere – driven by the low entropy free energy from the sun.

While Kauffman's real interest is in the *consequential* effect of complexity or order – 'Order for Free' [35] – he properly connects it with the thermodynamic causes. His 'small print' at the end of Chapter 4 makes this clear: '... while I have called it order for free ... it is not "for free" thermodynamically' (p. 92). This leads us on to an intriguing interpretation of (biological) evolution away from the idea of accident or marginality, and towards the concept of a synthesized biothermodynamic enterprise.

We suggest that this could be described as a 'thermodynamic imperative', inspired by a comment made by Brooks and Wiley. 'We do not assert that energy flow is trivial', they admit (p. 34), 'only that there is no external energetic imperative behind organismic diversification'. However, it is our belief that this decoupling of biology from 'energetic' thermodynamics is not only unnecessary but also difficult to justify, particularly as, like Kauffman, they make the connection with free energy. In this regard we read (their p. 48), 'if free energy is used to maintain, transmit and express biological information, we assume that information must be subject to thermodynamic constraints and *expectations*' (our italics). In so saying, Brooks and Wiley point towards the very imperative they deny. We have previously suggested that by re-interpreting their 'entropy' as 'complexity', their whole approach can be broadly made consistent both with their fellow biologist Kauffman and the thermodynamicist Wicken. Further, we conclude, that a thermodynamic imperative may indeed be postulated.

8.3 *Homo sapiens* the engineer

We have considerable empathy with Kauffman's approach. Our rationale is somewhat different and possible complementary. We have endeavoured to be as conservative as possible in applying engineering thermodynamics to biological organisms, by using the whole logic of the industrial revolution in reverse. So the 'closed system heat engine' is given an 'open cycle thermodynamic engine' partner applicable to both engineering and biological systems. This is seen at its clearest in comparing engineering locomotion with draught – animal locomotion. Both use free energy as input, both provide work as output, so being termed 'work engines'. Most species do no *net useful* work and are thus termed 'survival engines'. Kauffman's bacterium ([35], pp. 7, 8), while generating thermodynamic work cycles with its flagellar motor, is doing it exclusively within the food chain. Our distinction between this (technically correct) work and net useful work is also implied by Kauffman in the statement 'sense of "useful" outside the context of autonomous agents' ([35], p. 91). Like Kauffman, Wicken, and Brooks and Wiley we have focused on information, but in our case this is exosomatic (to use Goonatilake's descriptor) or Shannon

information/complexity (after Wicken). Hence *Homo sapiens* becomes a ‘complexity engine’ par excellence or by further using eucultural in addition (after Lumsden and Wilson/Goonatilake ([25], p. 31)) the *only* ‘complexity engine’.

Also a final key point is, that because *Homo sapiens* converts free energy to Shannon information, the latter can become a true thermodynamic variable. This logic points to some resolution of the arguments about ‘Shannon entropy’. In principle, it would be possible to make a conversion quantification between net entropy gain and increase in complexity.

8.4 Concluding comments

Several, more points need to be made. Firstly, the timescale of our biological engines is an engineering rather than evolutionary one, with a dominant cycle period of 24 h. A part of the free energy input must go into Kauffman’s ‘expanding phase space’ on an evolutionary/natural selection timescale.

Secondly, because the biological engine open system is still a black box, it can also accommodate a cumulative hierarchy of communities, not just individual organisms. As the hierarchy ascends, such communities develop into the biosphere itself. In this way, Kauffman’s ‘fourth law’ focus on the biosphere could be reconciled with that of Wicken, either by Kauffman re-expressing it for a closed system, or by Wicken extending his thermodynamic treatment to open system organisms. The former is probably thermodynamically preferable because simpler.

Finally, this gives an intriguing parallel path situation for evolution. Genetic development may occur in two ways – either via natural selection, or through *Homo sapiens* ‘tinkering’ with the biology (after [27]). Hawking puts it more dramatically. ‘Now we are at the beginning of a new era, in which we will be able to increase the complexity of our internal record, the DNA, without having to wait for the slow process of biological evolution’ ([26], p. 165). *Homo sapiens* has become a complexity engine indeed!

9 How mathematical is biology? How chaotic is evolution?

9.1 Introduction

I wrote to Professor Miller, of Cambridge, and this geometer ... tells me that it is strictly correct. If a number of equal spheres be described ... there will result a double layer of hexagonal prisms ... the same with the best measurements which have been made of the cells of the hive – bee.

Charles Darwin [9], pp. 173, 174

Physics seems to be mostly sums, biology mostly essays. I like biology better than physics, but I’m better at sums than I am at essays. Anyway, my best friend is going to do biology, so I can keep asking him ... That does it – I’ll do physics.

Eric Laithwaite [37], pp. xi, xii

I will not need to use in this book any more mathematics than can be expressed in words than in abstruse equations.

Philip Ball [38], p. 14

'Mathematical Biology'

James Murray [39], Title of book

The rationale for the three chapters we have written is that of a biological/thermodynamic synthesis which has been largely accepted into mainstream thought. Here we wish to extend our consideration to the idea that the synthesis should also include *mathematics*. Of necessity our discussion must be brief and we feel that the material, although convincing to us, is best expressed as questions and not postulations.

The general relevance of mathematics to nature was discussed in the main Series Introduction in Volume 1. While biology's public face is that of an experimental science (Darwin consults with Miller rather than jointly researching with him) there are now clear indications of a possible holistic mathematical basis. This is especially represented by the massively comprehensive studies of Murray [39] stemming from reaction–diffusion systems. This really harks back to the celebrated analysis of pattern formation by Turing dating from 1952 [40]. This was recently nicely assessed by Maini [41]. Maini, in fact, closes our thermodynamics circle, pointing out the connection between reaction–diffusion (or activator–inhibitor) systems and dissipative structures of Prigogine.

Mathematically (see Maini for a concise explanation) such equations exhibit diffusion-driven instabilities which result in stable pattern formations – a kind of 'order out of chaos' or emergent property, where complexity results from an 'integration of fundamental units'.

Overall, the above points to the possible synthesis of thermodynamics, mathematics and biology into a kind of extended Prigoginian model. We could describe this by:

Living systems maintain their far-from-equilibrium state by extracting free energy from, and rejecting heat to, the environment. The energy so gained dissipates itself in a chaotic manner (sometimes termed deterministic chaos) and results in an eventual increase in complexity.

This much can, we believe, be described as a mainstream thermodynamics/biology interpretation which points towards the involvement of chaos-oriented mathematics. For example, there is increasing evidence that the internal system behaviour of *Homo sapiens* is of a chaotic (non-linear dynamic) manner. In this context see [42, 43] relating to the cardiovascular system, in a journal special issue on Chaos published in March 2006. Also, Alzheimer's and Parkinson's diseases are being investigated along similar lines [44]. Such behaviour does not so much prove the above model, but rather that the model is consistent with current medical evidence. In the same way it is consistent with Ji's previously-discussed implications of a chaotic descriptor of overall human behaviour. While the core message of this chapter is that living organisms may be fairly regarded as *operating thermodynamic systems* there is increasing evidence that this has a mathematical character.

9.2 Self-organization: a new keyword

We now wish to extend the applicability of chaos theory to general biology. We remind ourselves that the same power source (thermodynamics free energy) that permits living systems to operate also 'drives' morphogenesis and evolution itself. This fact represents a *prima facie* case that the same principles applying to our day-to-day existence as living organisms, could also apply to the biological processes (whether developmental or evolutionary) that brought such existence into being.

This brief review is introduced with the well-accepted work of Turing [40]. This concerned pattern formation and morphogenesis. Combined with Murray's subsequent studies, Turing's

approach firstly provides a mathematical basis for *surface pattern formation* for organisms. Certain shell patterning, as pointed out by Ball ([38], p. 89), has no survival implications, and so is free of natural selection as a driving mechanism. Most patterning, however, whether of cats and zebras (Futuyama ([45], p. 43); Ball ([38], pp. 84–88)) of angel fish (Wolpert *et al.* ([46], p. 317 or Ball (pp. 93, 94)) or of butterflies (Ball (pp. 94–99)) does have survival effects, and this means that *both* natural selection *and* ‘mathematics’ simultaneously contribute to the end result. In the case of the angel fish, development is involved in the patterning too. This is obviously potentially a most important conclusion, which Futuyama describes ([45], p. 431) as ‘an example of possible constraints on the phenotype arising from physical chemistry’.

Now the expression ‘mathematics’ has been used above as a cause complementary to natural selection. Turing postulated that in an initially uniform chemical mixture, the processes of diffusion and auto-catalytic chemical reaction could result under certain conditions, in forms of patterning. This reaction diffusion system could be solved via a partial differential equation. Ball, who gives an excellent non-mathematical explanation in [38] (p. 79, 80) describes [40] as ‘undoubtedly one of the most influential in the whole of theoretical biology’. A rather fine description with attractive diagrams is also given by Wolpert *et al.* ([46] p. 317). Wolpert *et al.* give the important caveat of ‘as yet no direct evidence’. Harold, on the other hand, in his extensive review of morphogenesis in micro-organisms [47] points out that some of the resultant patterns ‘bear an uncanny resemblance to biological ones’ (p. 414).

At the start of his treatise, Murray ([39], p. 1) gives the generic PDE as:

$$\frac{\partial u}{\partial t} = f(u) + D\nabla^2 u,$$

where u is the reactants vector, $f(u)$ is the non-linear reaction kinetics, and D is the diffusivity matrix.

It is important to realize that the above equation is only ‘obeyed’ in the sense that it aims to be a high fidelity conceptual representation in quantitative terms of what is actually a fundamental mode of physical behaviour (Futuyama’s ‘physical chemistry’). In fact, in biological terms ‘activator–inhibitor system’ is used (see, e.g. [38, 46]), and the process is termed ‘self-organization’. As is apparent from Table 1 the expression has become a new keyword.

To conclude this section, we need to make the statement ‘*both* natural selection *and* self-organization simultaneously contribute to the end result’.

9.3 Self-organization (mathematics, chaos theory): how powerful an effect?

... I don’t believe I am saying anything that will disturb molecular biologists ...

Philip Ball [38], p. 9

This undoubted instance of the inheritance of acquired characteristics leaves both the theory of evolution by natural selection and the central dogma quite unscathed, but has important implications for the inheritance of form.

Franklin Harold [47], p. 387

If Kauffman is correct, the dynamic states of interacting genes also generate domains of attraction, or cell types.

Rudolf Raff [49], p. 330

Table 1: Self-organization – a new keyword.

Author	Title	Detail
Harold, F.M., 1990 [47]	To shape a cell: an inquiry into the causes of morpho- genesis of microorganisms	[Self-Assembly] 'a single principle of morphogenesis universally acknowledged by bio- chemists and cell biologists' (p. 393) [Self-Organization] Section Heading (p. 413)
Kauffman, S.A., 1995 [48]	<i>At Home in the Universe</i>	The Search for the Laws of [Self-Organization] and Complexity (sub-title)
Webster, G. & Goodwin, B. 1996 [29]	<i>Form and Transformation</i>	<i>Phyllotaxis</i> as a [Self-Organising] Growth Process. Section Heading (p. 215) 'an ... unresolved tension between principle of [self-organization] and natural selection' (p. 23)
Raff, R.A., 1996 [49]	<i>The Shape of Life</i>	'results of developmental genetics show that [self-assembly] in itself is an incomplete model for ontogeny'
Wolpert, L. <i>et al.</i> , 1998 [46]	Principles of development	'[Self-organization] may be involved in pattern formation in the limb bud', Section 10-9 (p. 315)
Ball, P. 1999 [38]	<i>The [self-made] tapestry – Pattern Formation in Nature</i> (Book Title)	

If, then, there appears to be general acceptance that self-organization à la Turing (and, in its wake, mathematics and chaos theory) has a real part to play in morphogenesis, and if in the reverse direction, enthusiastic supporters like Ball and Harold maintain a neo-Darwinian orthodoxy, why is there a strong element of controversy?

Table 2 attempts to summarise the debate by way of cross-referencing research workers with a number of recent and definitive publications. The workers comprise D'Arcy Thompson (the originator of the idea of form being defined not just by evolution but also by forces [52]) Turing himself, and the proponents of self-organization/mathematics/chaos theory – Murray, Kauffman and Goodwin. Prigogine is also included, in consistency with our overall thermodynamic context. Finally, plant phyllotaxis appears, as that has the same rationale of self-organization (Webster and Goodwin [29], figure 1).

The controversy exists for the following reasons. On the one side, the general acceptance implied by Table 1 is too strong an expression in the light of Table 2. So Futuyama writes 'possible constraints' ([45], p. 431). So Wolpert writes 'may be involved', 'there may therefore be', 'one possibility is' ([46], pp. 315–317). On the other side, Goodwin in particular is convinced, that 'there are some fundamental aspects of an organism's form that persist *in spite of* natural selection', and of 'features that evolution is powerless to erode away' ([38], p. 9). This is referred to by Raff as a 'strong version' of the 'structuralist hypothesis' which he finds 'somewhat startling' ([49], pp. 312, 313). Further there is Goodwin's (to Raff) 'most extraordinary statement of this view' to do with the common supposed generation of 'the mouth of ciliate protozoa such as

Table 2: How mathematical is biology? References to some significant research workers.

Publication	Research workers referenced					Plant
	D'Arcy T.	Turing	Prigogine	Murray	Kauffman	Goodwin
Futuyama, 1986 [45]	p. 422	p. 429	–	p. 430/431	–	–
Harold, 1990 [47]	p. 393	p. 414	p. 414	–	–	p. 423
Goodwin, 1994 [50]	p. xiii	p. 97	–	p. 135, 150, 226	p. 171 f.	na p. 105f.
Webster & Goodwin, 1996 [29]	p. 116	p. 199	–	p. 199	p. xiv	na p. 215
Raff, 1996 [49]	–	–	–	(p. 471)	p. 179, 298, 329	p. 298, 312 na
Wolpert <i>et al.</i> , 1998 [46]	–	p. 317	–	–	–	–
Ball, 1999 [38]	p. 6f	p. 78 etc	p. 81 f., 255	p. 96, 102	–	p. 9 p. 104
Purves, <i>et al.</i> , 2001 [22]	–	–	–	–	–	–

Notes:

1. Discussions (verbal/written) with Wolpert referenced by: Murray ([39], p. 75), Raff ([49], pp. 312, 313), Goodwin ([50], p. vii), Webster and Goodwin ([29], p. 136f).
2. Goodwin, Kauffman and Murray have collaborated – see Goodwin, Kauffman and Murray [51], referenced by Webster and Goodwin [29] (p. 233).
3. Goodwin, in particular, has encountered the sharp disagreement of Raff (see above), and others (Ball [38], p. 9).

Tetrahymena, and the dorsal lip of the blastopore in amphibia'. Raff finds 'no support in the data for a strong version of structuralism' (p. 313). This sounds damning, but it is telling to compare Raff's reaction to that of Harold's. In the same subject area of ciliate protozoa, Harold registers 'Goodwin's remarkable proposition that the diversity of ciliate shapes can be encompassed by a simple mathematical formula, Laplace's general field equation' [47], p. 423).

Harold's consistent rationale is that generic specifications and morphogenesis are only 'linked quite indirectly' and that 'there appear to be few true morphogenes (genes dedicated to specifying shape) at least in microorganisms' (p. 386). Possibly consequently, he finds Goodwin's ideas stimulating rather than upsetting. Ball, too, is cautiously supportive ([38], p. 9) – 'it seems to me that (Goodwin's) arguments become weakened only when extended from specific instances to the status of a new developmental principle in biological growth'.

At this stage, we stress our diffidence in monitoring this biological debate. However, we do have an interest. One of us (M.W.C) is co-supervising a joint biological/engineering research project with Dr Dave Roberts of Natural History Museum, London in just this subject area. Specifically, it is the investigation of a possible generic body plan for especially, the ciliate protozoon *Tetrahymena*.

9.4 Self-organization and thermodynamics

Table 2 shows that the only texts referring to Prigogine are those of Harold and of Ball. In fact, the underlying intellectual material of the current chapter can also be gained in a biological context by studying the 50 pages of Harold's review, combined with the 16 pages (pp. 252–267) of Ball's last chapter. Ball includes much stimulating comment on the role of attractors, and of noise and robustness, topics which we have omitted for brevity's sake. The stance of Ball and Harold reflect, we feel, the way in which we have raised the issue of the significance of mathematics in biology. Moreover, it is telling that once the thermodynamic contributions are accommodated the possible scientific consequences appear to be the same. Overall it tends to justify our suggestion of a thermodynamic/mathematical/biological synthesis.

9.5 Self-organization, chaos and evolution

In a way, this is an easy subject to review very briefly, as Kauffman's entire research enterprise focuses on this. We refer, for example, to his recent *At Home in the Universe. The Search for the Laws of Self-Organization and Complexity* [48]. His book 'describes my own search for laws of complexity that govern how life arose naturally from a soup of molecules, evolving into the biosphere we see today' (p. viii). To quote the blurb, '... the forces for order that lie at the edge of chaos ...', 'Kauffman extends this new paradigm to economic and cultural systems, showing that all may evolve according to similar general laws'. In the book we find consistent reference to the components of chaos theory – attractors, in particular.

It is certainly not just Kauffman. The very recent *Deep Simplicity. Chaos, Complexity and the Emergence of Life* by Gribbin [53] covers much the same field with a virtually identical approach. Also, the above mention of economic and cultural systems is expanded by, again, an entire book, that of Goonatilake *The Evolution of Information* [25]. In his case the chaos theory is highlighted by the presentation of biological and economic history as a series of bifurcations (p. 162). One or two brief quotes demonstrate the commonwealth of understanding Goonatilake shares with the other authors: '... dissipative structures operate, giving rise to evolutionary processes' (p. 167), and 'the deeper – level dynamics of the thermodynamic engine of open systems' (p. 168).

All in all, the proposed triple synthesis of Section 9.4 is extended by Kauffman and Goonatilake to include evolutionary processes wider than in biology.

10 Conclusion

This chapter completes our survey of the relevance of thermodynamics to biology, in the form of a trilogy of chapters. The first was in Volume 1 of the Design and Nature Series, and the others are in this volume. We have endeavoured to make them understandable for those ‘without previous knowledge’. In this chapter we have studied the key concept of the heat engine, which stems from the roots of thermodynamics in the Industrial Revolution. Moreover, by widening the definition to focus on *output* and on *open systems* it has proved possible to accommodate pre-Industrial Revolution machines and living organisms. The ‘black box’ character of the definition of the thermodynamic system makes this a relatively straightforward procedure.

By considering locomotion, it is possible to view draught animals (and *Homo sapiens*) as work engines and all species as survival engines. Also on this basis, *Homo sapiens* is the only ‘eucultural’ complexity engine, able to convert free energy input to exosomatic information output to a very high degree. The significance of this interpretation is investigated and related to the possibility of further laws of thermodynamics for living systems.

The dissipative structures of Prigogine’s thermodynamics necessitate the involvement of non-linear dynamics/chaos theory. An initial consideration is given to the question of how mathematical biology actually is. The assessment includes Turing’s and subsequent studies on pattern formation and morphogenesis.

We conclude that there is a convincing synthesis of thermodynamics and biology. This is the main message of our entire study. Also, we believe that the future may well see that the synthesis includes mathematics as well.

Acknowledgements

This chapter includes material adapted from a previous presentation by one of the authors, M.W.C.: Man the engineer – an interpretation of *Homo sapiens* based on engineering thermodynamics. Introductory address, 2nd International Conference on Design & Nature, Rhodes, Greece, June 2004. *Design and Nature II*, eds. M.W. Collins & C.A. Brebbia pp. xv–xx WIT 2004.

We are most grateful to Miss Monika Turska (assistant to Prof. Jan Antoni Stasiek) who prepared this chapter for publication.

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