Information and Thermodynamics in Living Systems

Andy C. McIntosh

School of Process, Environmental and Materials Engineering, University of Leeds, LEEDS, U.K. LS2 9JT, a.c.mcintosh@leeds.ac.uk

Abstract

Are there laws of information exchange? And how do the principles of thermodynamics connect with the communication of information?

We consider first the concept of information and examine the various alternatives for its definition. The reductionist approach has been to regard information as arising out of matter and energy. In such an approach, coded information systems such as DNA are regarded as accidental in terms of the origin of life, and it is argued that these then led to the evolution of all life forms as a process of increasing complexity by natural selection operating on mutations on these first forms of life. However scientists in the discipline of thermodynamics have long been aware that organisational systems are inherently systems with low local entropy, and have argued that the only way to have consistency with an evolutionary model of the universe and common descent of all life forms is to posit a flow of low entropy into the earth's environment and in this second approach they suggest that islands of low entropy form organisational structures found in living systems.

A third alternative proposes that information is in fact non-material and that the coded information systems (such as, but not restricted to the coding of DNA in all living systems) is not defined at all by the biochemistry or physics of the molecules used to store the data. Rather than matter and energy defining the information sitting on the polymers of life, this approach posits that the *reverse* is in fact the case. Information has its definition outside the matter and energy on which it sits, and furthermore *constrains* it to operate in a highly non-equilibrium thermodynamic environment. This proposal resolves the thermodynamic issues and invokes the correct paradigm for understanding the vital area of thermodynamic/organisational interactions, which despite the efforts from alternative paradigms has not given a satisfactory explanation of the way information in systems operates.

Starting from the paradigm of information being defined by non-material *arrangement* and *coding*, one can then postulate the idea of laws of information exchange which have some parallels with the laws of thermodynamics which undergird such an approach. These issues are explored tentatively in this paper, and lay the groundwork for further investigative study.

Keyword: Information, thermodynamics, free energy, organisation, entropy, open systems, machines, biopolymers

1. Introduction

In 1981 Kenneth Miller of Brown University commenting on the famous Stanley Miller-Harold Urey [1] experiment made an assertion concerning the laws of thermodynamics and the origin of life, particularly as it pertains to the formation of the nucleotide Adenine ($C_5H_5N_5$, see Figure 1), one of the nucleotides needed in living systems, from Hydrogen Cyanide (HCN), (the part of this quote in square brackets has been added to clarify the context of the remark) [2]:

> All this needs is energy in the system, adenine is far more complex than hydrogen cyanide. It forms. Why? Because it's consistent with the second law [of thermodynamics], which says you can have an increase in complexity if energy is available for the system. And you know what's remarkable? Adenine is the most important base in living things and it is the first thing that forms, and it forms easily.

The essence of the throw away remark "all this needs is energy in the system" is an appeal to the natural laws of nature to produce, in the end, the structures necessary to create life. It has often been used in the debate on origins when it comes to the thermodynamic issues. Kenneth Miller was not saying that the Miller-Urey experiment had proved conclusively that life could be formed from a mixture of water, methane, ammonia, and hydrogen. However he was stating that such examples of nucleotide production are demonstrations that a useful structure could arise spontaneously as long as enough energy is available. The idea that all one needs is to 'just add energy' is considered in this paper along with the issue of information.

John Sanford of Cornell commenting in some of his introductory writings for this conference on the progress made since the human genome was mapped in 2001, has stated [3]

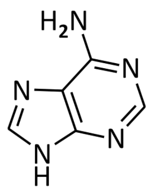


Fig. 1. The chemical structure of Adenine ($C_5H_5N_5$) — Some have argued that Hydrogen Cyanide (HCN) was the precursor to forming this important nucleotide in origin-of-life scenarios.

> "Few anticipated the astounding discoveries of the last ten years, which have revealed that biological information, even in simple cells, is much more complex than we could have even imagined. Indeed, we now realize that the simplest free living organism reflects a virtual labyrinth of information. A single cell represents layer upon layer of information, each layer of information being encrypted within a great diversity of molecular types, each type of information being encoded via its own set of linguistic signals. Within a single living cell is an active communication network something like the internet, and what we can see of this "biological internet" is expanding daily. This is forcing many scientists to reexamine our earlier understanding of biological information. Even while the amount of biological complexity requiring explanation has been expanding exponentially, the traditional explanations of biological information have been unraveling".

The concept of information has in fact been a major issue since the discovery by Francis Crick and James Watson of the coding structure of DNA in 1953. Crick himself stated [4]

> "If the code does indeed have some logical foundation then it is legitimate to consider all the evidence, both good and bad, in any attempt to deduce it."

This was stated in the context of the discovery that triplets of nucleotides running along the rungs of the double helix molecule of DNA carry information to code for a specific amino acid which then makes up the proteins of the living organism. Crick was always of a reductionist mindset and had no sympathy with any approach which regarded the coding as essentially an expression of a non-material intelligence transcendent to the polymer itself, and the above statement in its original context is most definitely not advocating an exploration of information in any other paradigm than a purely materialist approach. However it is significant because it shows that scientific investigation can be trapped by only considering one pathway — what if the search for a 'logical foundation' advocated by Crick, actually leads one to the *edge* of the material region of scientific enquiry?

Stephen Jay Gould wrote of non-overlapping magisteria [5], often referred to with the acronym NOMA, in order to resolve the issues of how to approach both science describing the physical realm and the metaphysical/philosophical concepts describing realities which are essentially non-material. This is diagrammatically shown in Figure 2.

However such an approach to reality means that in investigations of the area of information and software/mind and consciousness, this view incorrectly locks the investigator into a materialistic approach which at the outset denies *per se* the most persuasive explanation of the intricate systems which have come to be understood

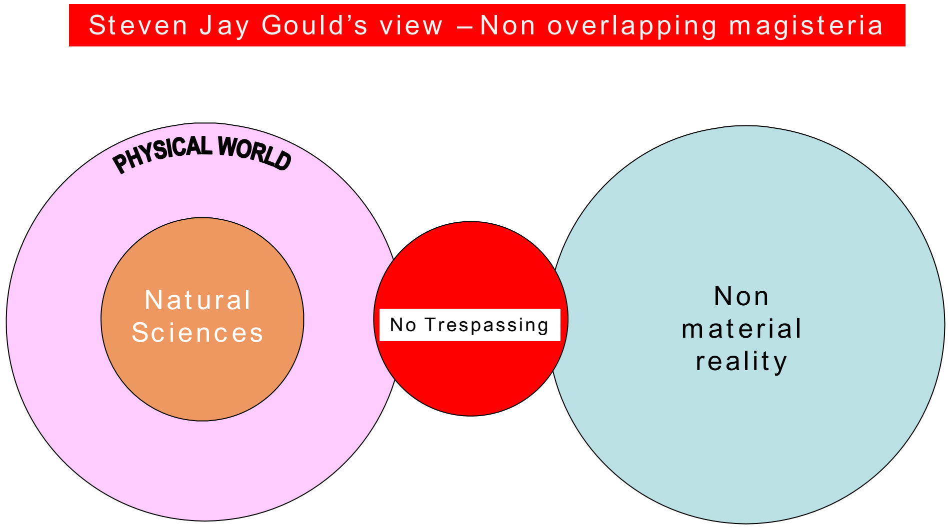


Fig. 2. Stephen Jay Gould's non-overlapping magisteria (NOMA) view of reality.

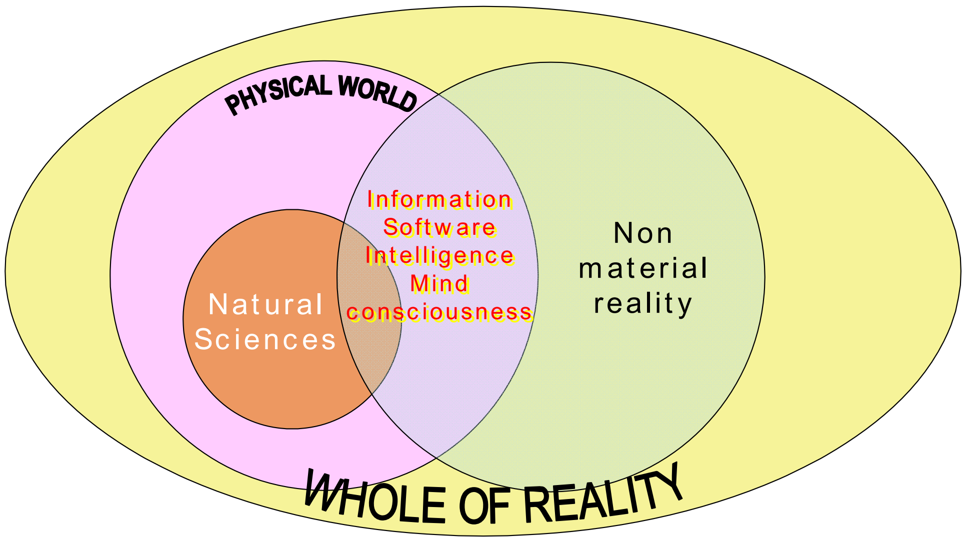


Fig. 3. The view of reality advocated in this paper which defines information as constraining the matter and energy it sits on, but not defined by it.

in recent years. The antithesis to Gould's approach is illustrated in Figure 3. It is argued that there is a legitimate realm where information, mind and consciousness lie — this area is undoubtedly interacting with the physical realm but is not entirely controlled by it. Though this clearly can have metaphysical implications, we are here not talking about religious matters, but simply the area where thoughts, logic and mind exists, and where the importance of *arrangement* rather than *matter* itself is dominant — as for instance in the sequencing of the nucleotides in DNA.

The paradigm adopted here is the assumption that information is essentially defined as non-material but profoundly influences the material in which it is found, in a similar way that software is essentially coded non-material instructions but nevertheless controls the hardware of a computer. It should be emphasised that this is not a license for any lazy thinking, whereby anything which cannot be understood is put metaphorically into a box labelled 'non-material and not to be further investigated'. This is no 'god of the gaps' thesis. Indeed, once adopted, this approach opens out a whole raft of new research routes which properly explain the control of living systems. A far more profound methodology is in view. What is being advocated here is an entirely different paradigm whereby the non-material message is accepted as being of an origin outside the area of physical investigation, but that its effect can readily be seen in the organisation of the molecular machinery in living organisms. Rather than the material and energy forming the information system as advocated by evolutionary philosophy, the non-material informational message expressed in the coded ordering of nucleotides is actually the mechanism of constraining the material itself. In this paradigm, it is the information which *organises* and *constrains* the biopolymers. It is a known feature of living systems that they are information-rich and it is this that is more and more being recognised as the cause of their great efficiency [6]. Rather than the intricate machinery for such systems evolving from simpler systems, it is the thesis of this paper that the message/information itself is sitting on biochemical molecular bonds which are in a significantly raised free energy state. Understanding the thermodynamics of this machinery shows that it is thermodynamically impossible both to form such machinery (abiogenesis) without intelligence, and that the laws of thermodynamics prohibit any formation of new machinery which is not there already or latently coded for in the DNA (evolutionary development). A hierarchical system of information is involved in living systems (see Figure 4).

Furthermore recent research has confirmed that non-coding parts of DNA previously thought to be 'junk DNA' are in fact not to be regarded as such [7]. More research is now coming to light [8] that the very folding of proteins carries with it a separate form of information transfer. This intertwining of information and matter lies at the heart of what is life itself, and fundamentally changes our view of how to understand living systems.

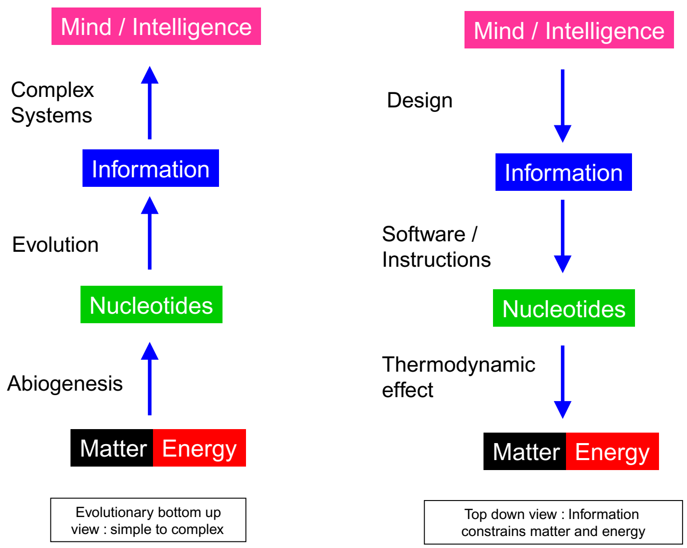


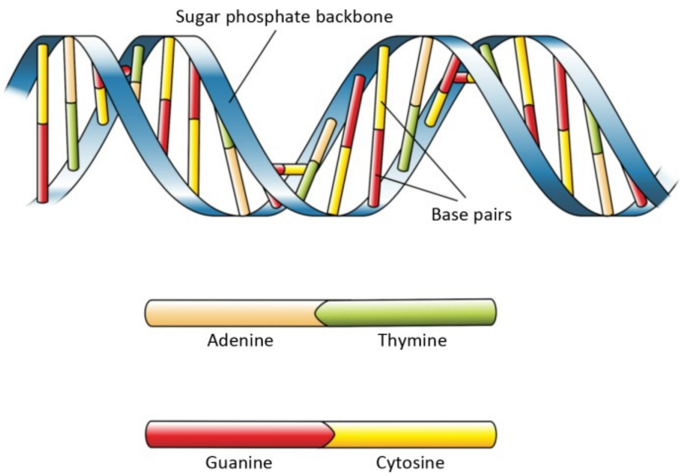
Fig. 4. Hierarchical layering of living systems. The evolutionary view is that abiogenesis led to the forming of the DNA code which then led to the emergence of complex information systems and intelligence. However the top down view regards information in a similar way to the software instructions of a computer. The instructions organise the nucleotides and control the biopolymers to be in a highly non equilibrium state.

2. Biological information storage and retrieval — thermodynamic issues

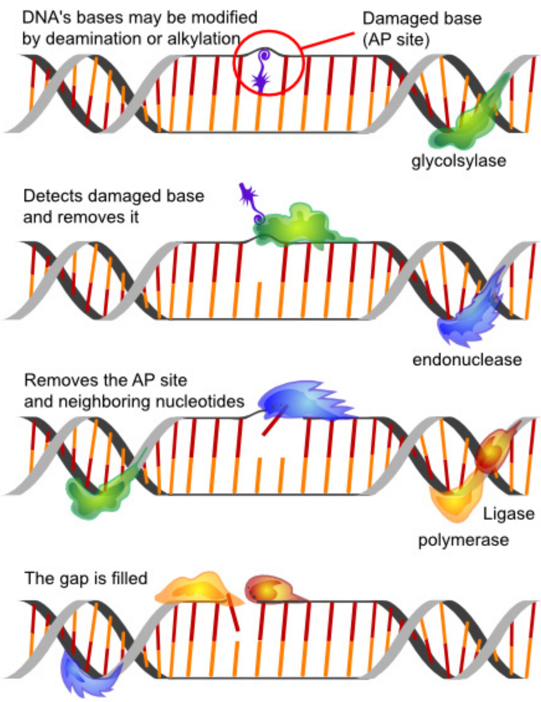
There are major thermodynamic hurdles in arguing that the emergence of DNA (see Figure 5a) could come about by a random gathering together of the sugar phosphates and nucleotides. These are discussed in greater detail elsewhere [9,10].

In essence evolutionary arguments for the origin of information (e.g. Dawkins [11]) amount to appealing to random mutations as a means of increasing the range of possible phenotypic outcomes. The further appeal is often made to the concept of 'Shannon information', which idea comes from the basis that increased uncertainty can lead to a richer number of possibilities in a signal. This is sometimes termed Shannon entropy [12], but as shown in ref. [10], is in many ways the opposite of what is really needed, since it is really a measure of the spread of mutations at the nucleotide level, and these mutations are virtually all deleterious [13].

There are two major obstacles to such a proposal. First the code is highly sequence specific. Each triplet of nucleotides codes for a specific amino acid and the protein formed from these requires a specific sequence of such amino acids. For example there are enzymes which are *specifically* assigned to nucleotide excision repair — they recognise wrongly paired bases in the DNA nucleotides



(a)



(b)

Fig. 5. (a) DNA is a double helix formed by base pairs attached to a sugar-phosphate backbone. This then forms a series of triplets of nucleotides on the main (message bearing) strand and complimentary nucleotides on the opposite strand. The connection is by a weak hydrogen bond A–T and G–C. (b) DNA base excision and repair is performed by three enzymes. Glycolsylase first finds the damaged site and the nucleotide, and then endonuclease removes neighbouring bases. Then the protein DNA polymerase manufactures the appropriate nucleotide and the enzyme ligase encircles the damaged DNA, and the replacement nucleotide base is put in place. [DNA repair image (public domain) from www.clker.com.]

(Adenine (A), Thymine (T), Cytosine (C) and Guanine (G)) connecting the two deoxyribose sugar-phosphate strands (see Figure 5a). This is summarised in Figure 5b where the excision and repair of a damaged nucleotide base is shown. First the enzyme Glycolsylase finds the damaged site and the nucleotide, and then endonuclease removes neighbouring bases. Then the protein DNA polymerase manufactures the appropriate nucleotide and the enzyme ligase encircles the damaged DNA, and the replacement nucleotide base is put in place. This means that mutations are generally corrected (Jackson [14] and de Laat *et al*. [15]), so that even if speciation does occur due to slight modifications and adaptations of the phylogeny, any serious departures in the genetic information would be acted against by the DNA's own repair factory. Mutations generally do not increase information content — rather the reverse is true.

The second obstacle is a more fundamental issue. At the molecular level, the principles of thermodynamics do not permit the formation of new machinery from that which is already set up or coded for in a particular function performed by the cells of living organisms. There is in fact an 'uphill' gradient in the formation of any of the molecular bonds in the nucleotides and most of the proteins, since they want to pull apart. Consequently there is no natural chemical pathway to form these, rather there is a move away from their formation to equilibrium. In the following sections we examine the thermodynamic principles governing living systems.

2.1 *Thermodynamics and isolated systems*

One form of the statement of the second law of thermodynamics is "The amount of energy available for useful work in a given isolated system is decreasing. The entropy (dissipated energy per degree Kelvin which can no longer be used to do work) is *always* increasing."

Thus according to the second law, heat always flows from hot to cold. In the process it can be made to do work but always some energy will be lost to the environment, and that energy cannot be retrieved. Water flows downhill and loses potential energy which is changed into kinetic energy. This can again be made to do work (as in a hydroelectric power plant). However some energy will be lost such that if one was to use all the energy generated to pump the same water back up to its source, it would not reach the same level. The difference of original potential energy to that corresponding to the new level, divided by the temperature (which in that case is virtually constant) is the entropy of the system. Such a measure will always give an entropy *gain*.

There is no known system where this law does not apply. The fact that the entropy of a given isolated system increases, effectively brings with it an

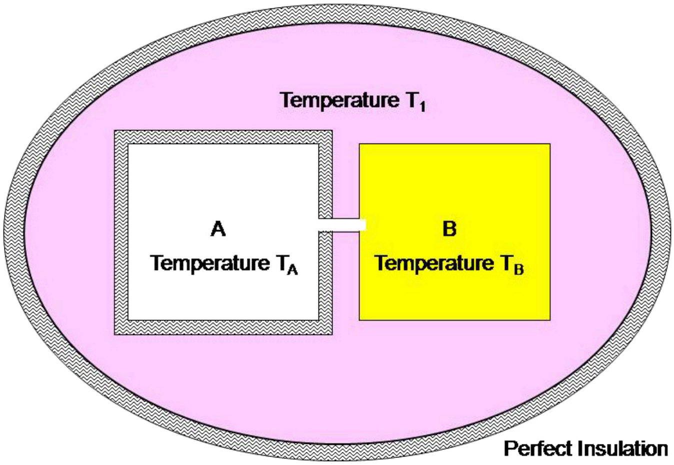


Fig. 6. Non-isolated system A and B

inevitable eventual decline in usefulness of all sub-systems within such an isolated system.

2.2 *Non isolated systems*

In that the second law of inevitable entropy increase applies to an isolated system, some have maintained that with a closed (boundaries open to heat transfer) or open system (boundaries open to heat and mass transfer) one could have entropy decreasing in one area while the overall entropy of the two systems together is increasing. An illustration would be of two ice boxes A and B (Figure 6) where there is an allowance for some small contact between them but with (perfect) insulation round the rest of the cube A and poor insulation round cube B. Systems A and B are both then non-isolated systems (technically closed as heat can pass the boundaries but not mass), as is the system A and B together (referred to as A+B), but system A and B with the surrounding region 1, (that is the complete system) is isolated. The entropy of the overall complete system then must increase with time. That is, there will eventually be equilibrium throughout every region.

2.2.1 *Entropy deficiency*

Suppose we start with Temperature T_1 appreciably hotter than T_A and T_B. Thus for instance we could have $T_1 = 100°C$ and T_A and T_B both at -10°C. Initially as time progresses the original equal temperatures T_A and T_B become different. T_A will stay close to the original −10°C, but T_B will begin to move to a higher value (say +5°C) due to there being good conduction of heat into ice box B (as against the insulated ice box A). Now consider system A and B together (A+B). One now has an open system with decreasing entropy called an *entropy deficiency*, in that useable energy transfer between the two ice boxes is possible, and work can be achieved where before in that system, treated in isolation, none was possible. However one notes two things. First that this is possible only for a finite time — eventually the temperature difference will reach a maximum (when T_B gets close to T_1) and at this point system A+B will have a minimum entropy condition. After this system A+B will then experience a rising entropy condition. Secondly one must insert some device between A and B before use can be made of this energy flow. This demonstrates the reality of how the underlying principles of energy flow and its use to do useful work, still apply in open systems. Extra energy is of no use *unless there is a mechanism to use it.*

2.2.2 *Open systems and machinery*

In the debate concerning origins where thermodynamic considerations are in view, much is made of the fact that the earth is an open system receiving energy and some mass transfer from extra-terrestrial sources. The main source of energy of course is the Sun. When one considers non-isolated systems where heat transfer can take place at the boundary, some have argued that by adding energy in to the original system then one should be able to reverse the overall trend of entropy increase. But this is not the case [10]. Adding energy without an existing mechanism which can make use of that additional energy, generally leads to simply the heating up of the surroundings faster than would otherwise have been the case. There can be cases where differential heating can occur (in the atmosphere or in the earth where rock and soil have thermal conductivity differences) following the same principle as outlined in Figure 6. Locally the entropy ($\Delta Q/T$ where ΔQ is the heat gained by the system being considered and T is temperature) can increase at different rates and give rise to a deficiency in entropy in one location compared to another. This can then potentially give rise to free energy which can do work. Thus for instance Freske [16] considers the entropy deficiency that sometimes can occur in a pile of bricks or rubble receiving energy from the sun, and that a device could make use of that energy supply

> …. under the given conditions, an entropy deficiency is in fact generated in the pile. After several hours of exposure to the sun, the temperature will be higher at the top than at the bottom. If we were to measure the temperatures throughout the

pile, it would be a fairly simple matter to calculate the entropy deficiency. Useful energy could actually be extracted from the pile by means of a thermocouple, for example.

The last sentence concerning energy extraction actually demonstrates that the point at issue is not so much whether deficiency in entropy can take place and thus useful energy can be made to do work, so much as *the capacity to use the energy available*. Whether it is capturing directly the energy input from the sun, or harvesting the differential energy flow due to entropy deficiency, *a mechanism for making use of that energy flow is essential*. Without the thermocouple in Freske's illustration, very little will happen without directed purpose behind it.

In Section 3.2 below, we define a *machine* as a functional device that can do work [10], and it then follows that only by having in existence such a mechanism for capturing the incoming energy, can further useful work be achieved.

2.3 *Can negative entropy be harvested from somewhere else?*

Prigogine [17] and others (see for instance Styer [18]) have proposed that there is information in the non-material arrangement and organisation of systems and refer to an organisational entropy or 'logical' entropy. They propose the addition of other entropies which could then feed negative entropy into a given (non-isolated) system. Consequently the total entropy is considered to be

$$ds = ds_T + ds_{\text{logical}} \tag{1}$$

where ds_{logical} represents the ordering principle or 'logical' negative entropy which gradually seeps in to the system. Thus even though ds overall is increasing with the thermal entropy ds_{T} positive, the presence of ds_{logical} coming in at the boundary ensures locally the low entropy needed to spark evolutionary development. Styer [18] speaks of a net entropy flux at the earth which would then be the source of evolution of early prokaryotes (cells reckoned to be primitive with no nuclei) to eukaryotic (cells with nuclei) individuals.

Thus complexity and the ordering principle is predicated on the notion that information can gradually increase from a random state. Again this is flawed for two reasons:

(i) Firstly as stated above in Section 2.2.2, no flux of energy from outside the system can be made to do work within the system unless there is the necessary machinery to capture this energy [10].
(ii) Secondly the information itself (that is the message and meaning behind the communication) is not defined in purely thermodynamic terms or even in any ordered code such as in DNA when considering biological systems. Gitt [19] has shown that information is hierarchical in at least five levels. Two important levels are code (or language) and message which uses the coded communication system. Neither of these can actually be thought of as arising simply from a flux of entropy locally. Rather the reverse of this is the reality, viz. that non-material information (that is arrangement and coded instructions) sits on a material substrate in living systems and *the non-material information arrangement/coding causes a thermodynamic effect.*

3. Free energy and Machines

In order to propose an alternative understanding of the information in living systems, one of the key parts of the argument concerns the availability of energy to do work, coupled with the mechanism for harnessing of that energy.

3.1 *Free energy*

The Gibbs free energy g is defined as the net energy available to do work. It effectively takes away the unusable lost energy (associated with entropy) from the enthalpy h (which can be regarded as the total thermodynamic energy available). Thus

$$g = h - Ts, \text{ and } \Delta g = \Delta h - T\Delta s \qquad \text{(2a,b)}$$

3.2 *Machines and raised free energies*

As a consequence of the principles of thermodynamics applied to non-isolated systems [9,10] one can state that the following applies concerning the spontaneity of chemical reactions:

$$\begin{aligned} &\Delta g < 0 \text{ Favoured reaction} - \text{Spontaneous} \\ &\Delta g = 0 \text{ Reversible reaction} - \text{Equilibrium} \\ &\Delta g > 0 \text{ Disfavoured reaction} - \text{Non-spontaneous} \end{aligned} \qquad (3)$$

Fig. 7. All natural molecule formations are like magnets with the same pole facing each other such that if one lets the system 'go' they would pull apart: $\Delta g < 0$ (due to $g \equiv h - Ts > 0$). To set this system up — that is to keep the opposing magnets together work needs to be put in — the free energy change to bring them together is positive. In a similar way to bring the molecules together which form living polymers requires an *initial input* of ordered energy by another machine.

Consequently a positive free energy device cannot arise spontaneously. It always requires another operational machine to enable the free energy to be loaded/'primed', ready to do work. This can be illustrated in the example above (Figure 7) of two magnets with the same pole facing each other. Work needs to be put into the system to hold the opposing magnets together — the free energy change is positive — it is non-spontaneous, and the magnets want to pull apart. In a similar way to bring the molecules together which form living polymers requires an *initial input* of ordered energy to cause them to stay together. Δg is positive.

This leads to a definition:

We define a *machine* as a device which can locally raise the free energy to do useful work.

Even if material exchange was involved (and one had a completely open system), no amount of matter or energy exchange without information exchange would alter the fundamental finding (eqn (3)) concerning the spontaneity of chemical reactions.

Thus the free energy argument applies both to isolated systems with no contact with the surroundings and non-isolated systems. The latter include open systems where heat and mass can cross the boundary, as well as closed systems where just heat is allowed to cross.

One can now consider what happens if energy is added to a non-isolated system (as in Section 2.2) and it is evident that without a machine, the free energy to do useful work is not increased. *Certainly no new machine will arise simply by adding random energy into an existing system*. Furthermore the random energy input, though it may cause an internal energy flow (as in Figure 6), *will not do useful work unless an existing machine is present*. Thus with direct sunlight a solar cell is a machine in this definition, since it is a free energy device to convert solar energy to electricity in order to do work. A wind turbine uses energy from the wind to convert to electricity, but a tornado, though it produces entropy deficiency [Section 2.2.2 and Ref. 16], is not a machine since there is no functionality, but rather it is an example of naturally occurring differential dissipation of energy.

3.3 *Thermodynamic law of non-isolated systems*

The principle outlined in Section 3.2 concerning the importance of free energy has been discussed by Sewell [20] and can be expressed succinctly in the following thermodynamic law of non-isolated systems:

"In a non-isolated system, the free energy potential will never be greater than the total of that which was already initially in the isolated system and that coming in through the boundary of the system."

3.4 *Crystal formation*

Coming back to the biochemistry of DNA and the formation of the amino acids, proteins and all the ingredients of living cells, to suggest that reactions on their own can be moved against the free energy principle is not true, since that situation could not be sustained. The DNA molecule along with all the nucleotides and other biopolymers could not change radically such that a low entropy situation would emerge. Certainly the situation cannot emerge whereby a sustained and specific sequence of thousands of raised free energy states of different molecular bonds is held, without a final subsiding to a new equilibrium where the free energies are dissipated.

So some have argued that surely crystal formation is a counter example where low entropy is achieved and an ordering principle is obtained? Consider again eqn (2b). If ΔH is negative but ΔS is also negative, then one can get cases where the net change in Gibbs free energy ΔG is zero. These cases (as referred to in eqn (3)) are examples of reversible reactions, and particularly happen at conditions of change of phase such as water going to ice crystals at 0°C (273K) (Figure 8). The entropy reduction multiplied by the temperature exactly balances the drop in the enthalpy. That is in the case of crystal formation, $\Delta H = T\Delta S$. One can liken the ΔS in this equation to being the logical/geometric influence on the thermodynamics such that the order inherent

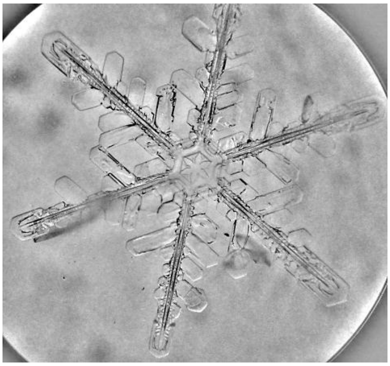


Fig. 8. Crystal formation — A snowflake (here viewed through a microscope) is an example where entropy is lowered as the phase change temperature is crossed, but the overall Gibbs free energy change is zero. The entropy reduction in crystallisation is simply a reflection of the geometry and the energy bonds already existing in the ions of the liquid phase as they connect up in the solid phase. The entropy reduction does not produce new order that was not latently there already. And most importantly there is no new production of a free energy device which can do useful work. (Image freely available from Wikimedia Commons, microphotograph by artgeek.jpg).

in the molecules themselves, given a low enough temperature, will cause the crystals of a particular shape to form. When such a compound is cooled to produce crystals, it is worth noting, however, that it is not the cooling itself which causes the crystals to occur, but the response to the molecular bonding which is very precise within the material and has a definite function of the state variables. Often this is regarded as demonstrating a new ordering principle emerging (and thus an argument for moving to functional form within a system), when in fact the ordering principle is latently already there in the structure of the chemical elements to begin with. And most importantly, there is no new production of a free energy device (a machine). The change in free energy is precisely zero, so there is no free energy device emerging that can do useful work.

3.5 Bio polymer formation

Now consider briefly the HCN → $C_5H_5N_5$ example that Kenneth Miller [2] discussed and we started with in the introduction. Given the right temperature and pressure in a container, Hydrogen Cyanide and energy from an electric spark will produce Adenine. Is this a gain in net free energy such that a molecular machine can be made? The answer is negative. Like crystallisation, the system is simply responding to external changes in temperature and pressure. Yes, it is producing Adenine and yes, Adenine is used as one of the nucleotides in DNA, but Kenneth Miller did not refer to the ensuing thermodynamic hurdles to then build the sugar phosphate bonds, the three other nucleotides, and the weak Hydrogen bonds which couple the paired nucleotides together (e.g. Thymine to Adenine) — all requiring positive free energy steps [21] (that is they will break apart if left to themselves). On top of this one has the homochirality issue. When Harold Urey and Stanley Miller [1] in 1953 managed to produce amino acids by passing an electric charge through a reducing atmosphere of methane, ammonia, water and hydrogen, they did produce amino acids with some (but by no means all) of the standard 20 amino acids which need to be coded for, in order to make the proteins for life. But the most important difficulty was that they produced both left handed and right handed chirality molecules in the expected 50:50 ratio. However, living systems have entirely left handed versions of these molecules (i.e. homochirality) which otherwise are identical in chemical behaviour. Living systems are not just to do with chemicals, but with the *shape* and *positioning* of the chemicals. Stanley Miller acknowledged that the difficulties were indeed formidable when in 1991 he stated to Scientific American [22] that 'the problem of the origin of life has turned out to be much more difficult than I, and most other people, imagined ...'.

Furthermore the latest work in DNA studies [23] has produced some astounding discoveries that Hoogsteen base pairing (where a different part of the nucleotide bases is temporarily used to connect the coding and complimentary parts of the DNA) constitute a second transient layer of the genetic code. They state

> …the DNA double helix intrinsically codes for excited state Hoogsteen base pairs as a means of expanding its structural complexity beyond that which can be achieved based on Watson-Crick base-pairing.

That is, there is already evidence that there is a further layer of information transfer in evidence — this again requires control of a suite of thermodynamic raised free energies by a different information system!

We stated in Section 3.2 that biopolymers could not change radically such that a low entropy and sustained sequence of free energies would emerge. To alter the DNA constituents from one stable state say to another representative state with a distinct improvement, cannot be done by natural means alone without additional *information*. The laws of thermodynamics are against such a procedure.

Put another way the carrier molecules of the information in living systems are actually kept in a non-equilibrium state by *the very presence of the coded information*. They would fall apart to a disordered equilibrium state were it not for the information in the system making them act in this way.

4. A different paradigm: Thermodynamics constrained by functional information

We thus propose a different treatment which quantifies the effect of functional information in a system. This approach recognizes Gitt's important deductions concerning real information systems being impossible to define in terms of matter and energy alone [19]. However one can recognise the effect of machines/information systems (that is teleonomy) being present in exactly the same way as a digitally controlled machine (i.e. a computer) is operated by software. The high level program controls a set of electronic switches on a micro chip which are set in a certain predefined pattern (see right hand part of diagram in Figure 4). Thus the logical negative entropy (the switching of the micro chip in the analogy) rather than being the *source* of the information should be thought of as the *effect* of information carrying systems.

Only with the presence of a free energy device (a machine already existing) will an energy flux outside the system do useful work and enable a local lowering of the entropy of the system. This is illustrated for photosynthesis in Figure 9 whereby it is evident that the machinery of the production of chlorophyll in the leaf acts as an important system for taking in Carbon Dioxide and forming sugars

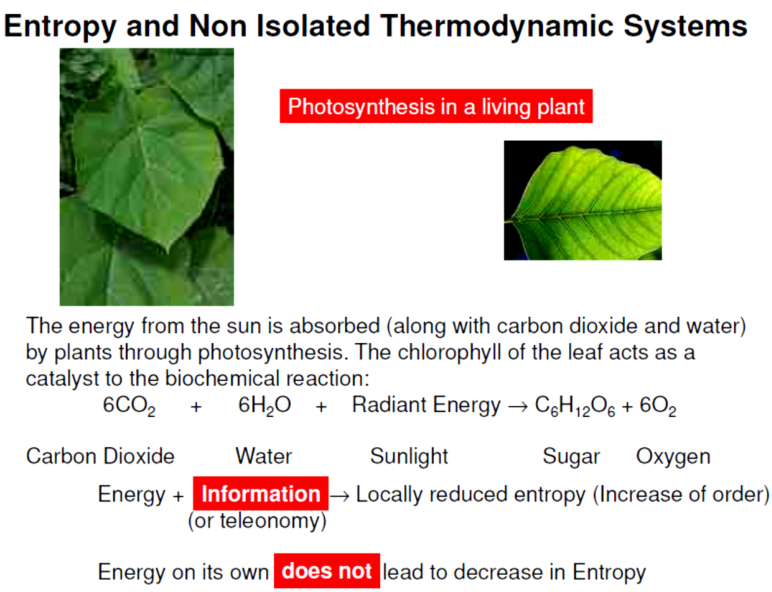


Fig. 9. Photosynthesis in a living plant requires energy input, but the energy flux on its own would do nothing unless there was a machine already present (a free energy device) to enable the system to do work using the sunlight.

and Oxygen. The energy flux on its own would do nothing unless there was a machine already present (a free energy device) to enable the system to do work using the sunlight.

In this approach it is expected that there will be levels of information, and in particular language (code) and semantics (meaning). This is a very different paradigm to that which is currently adopted, and leads to the proposition that machinery and information are closely intertwined in living systems [10,24,25], in a very similar way that software in a digital computer is intertwined with the electronic hardware and the very small but precise energy levels used in the computer registry, memory and storage facilities.

For a pure materialist there may be a natural reticence to adopting such an approach because of their presuppositions, but the evidence of the thermodynamics of living systems supports the view that it is *information* in living systems that controls the thermodynamics, and not the other way round.

4.1 *A different paradigm: Information definitions*

In order to construct a new approach to information exchange in living systems it is becoming evident that a new set of definitions is needed to set up this very valuable line of research. The following are suggested, and have come from valuable discussions with John Sanford [13] of Cornell University.

Information: That which is communicated through symbolic language.

Intelligent agent: An entity with the ability to create information and communicate it (i.e. — a human being).

Agency of intelligence: A secondary entity which is capable of being used to communicate information deriving from a higher source (i.e. — a computer).

Language: The symbolic medium through which information is communicated (i.e. Spanish).

Communication: The transmission of meaningful information through symbolic language.

4.2 *A different paradigm: principles of information and thermodynamics*

The following are suggested principles to understand the nature of how non-material information is transferred and communicated. In both the realm of thermodynamics and non-material information there are principles of conservation and degeneration. The following principles of information exchange are similar to the first two laws of thermodynamics and the thermodynamic law of non-isolated systems referred to in Section 3.3.

4.2.1 *Principles of information exchange*

We postulate the following principles of information exchange:

The First Principle concerning information, language, and communication
Apart from creative intelligence, information cannot be derived from nothing. There has to be a precursor bank of such information.

This is a parallel principle to the principle of conservation of mass and energy (first law of thermodynamics).

The Second Principle concerning information, language, and communication
Apart from a sustaining intelligence, all information degenerates in terms of its functional utility. Information will corrupt unless it is sustained by an intelligent agent.

This principle is a parallel to the second law of thermodynamics which effectively states that in a given isolated system, the energy available for doing useful work is diminishing — there is a principle of decay.

The principle of Information gain
The information content in a system is never greater than the total of that which was there already and that coming in through the boundary of the system.

This principle mirrors the thermodynamic law of non-isolated systems (Section 3.3).

4.2.2 *Principles of information interaction with energy and matter in biological systems*

We now summarize two further important principles which have been the main subject of this paper concerning the interaction of information with energy and matter in biological systems:

The First Principle of information interaction with matter in biological systems
Information in biological systems is expressed as coded instructions and is not defined by the energy levels or by the matter it resides in. It is not defined by the properties of that matter and is transcendent to it.

Comment: This principle is best exemplified by the fact that software in a computer is not defined by the hardware.

The Second Principle of information interaction with matter in biological systems
Information in biological systems constrains the matter and energy to be in a non-equilibrium state.

Corollary to second principle of information interaction
In biological systems all information sits on a substrate where a series of free energies are kept in disequilibrium. Thus information in biological systems relies on machines — that is on devices which raise the free energy.

Comment: This principle can be referred to as the 'top-down' principle — that is the information organises the thermodynamics of the system. The information does not arise out of the matter and energy.
Third principle of degeneration in living systems
Consequently the second principle of information interaction combined with the principle of thermodynamics decay, implies that degeneration, and in particular information corruption (mutations), will inevitably take place.

5. Conclusions

Three views of informational reality (ontology) are considered in this paper. The first is that matter and energy is all there is. This is the materialistic view of information (Dawkins (Oxford), Jones (University College, London), Atkins (Oxford) and others). Such authors argue that functional non-material information and design are an illusion. In their view matter and energy is all that there is in the Universe. Patterns only have meaning in a reductionist sense and do not carry any non-material 'value'. The second scenario is a variation of the bottom up approach. In this view information is regarded as non-material but has arisen out of matter and energy. This is the view of Prigogine [17], Yockey [26], Wicken [27] and Kenneth Miller [2,28,29] and many other authors.

Both these approaches are flawed on two counts. Firstly they ignore the fact that real information systems are *not* defined by the codes and languages they use and that the arrangement of the physical objects used in the system (for DNA, this would be the nucleotide triplets) has to be in a specified order. So even non-materialists such as Prigogine, Yockey, Wicken or Kenneth Miller have insuperable hurdles with such a system. By proposing an evolutionary model of the bottom up approach, they do not have the means to derive the specificity [30] in the ordering arrangement of the nucleotides in DNA. These issues are discussed in the work of Abel and Trevors [31, 32]. Secondly a more subtle point, but a very important one, is that there is an impossible thermodynamic barrier to such an approach. The information in living systems is mounted on molecules with a raised free energy such that the carriers of information would fall apart into equilibrium chemistry were it not for the information present. It is this barrier which shows that a top down approach is the only way to understand information in living systems.

The third view then that we have proposed in this paper is the top down approach. In this paradigm, the information is non-material and *constrains* the local thermodynamics to be in a non-equilibrium state of raised free energy. It is the information which is the active ingredient, and the matter and energy are passive to the laws of thermodynamics within the system.

As a consequence of this approach, we have developed in this paper some suggested principles of information exchange which have some parallels with the laws of thermodynamics which undergird this approach. They also have some profound implications concerning the inevitable decay in genetic material and the uniqueness of information in the beginning.

Acknowledgement

The author is indebted to many useful and profitable exchanges with Professor John Sanford of Cornell University. He has in particular suggested ideas for the principles on information exchange outlined in Section 4.

References

1. Miller SL (1953)Production of amino acids under possible primitive earth conditions. Science 117(3046):528–529.
2. Miller K.R., NCSE, The Miller/Morris Debate (1981), http://ncse.com/creationism/general/miller-morris-debate-1981 accessed January 2011.
3. Sanford J (2013) Biological Information and genetic theory — introductory comments. In: Marks II RJ, Behe MJ, Dembski WA, Gordon B, Sanford JC (eds) Biological Information — New Perspectives. World Scientific, Singapore, pp. 203–209.
4. Crick F "On the Genetic Code", Nobel Lecture, December 11, 1962 and also recorded in, Science 139(3554), 8 February 1963.
5. Gould SJ (1999) Non over-lapping magisteria. Skeptical Inquirer, July August, p55–61.

6. Vincent JFV, Bogatyreva OA, Bogatyrev NR, Bowyer A, Pahl AK (2006) Biomimetics: Its practice and theory. J Royal Society. Interface 3:471–482. In particular see discussion on p. 477 of nature's vast resources of information and small energy useage by comparison with man-made technology.
7. Birney E, *et al* (2007) Identification and analysis of functional elements in 1% of the human genome by the ENCODE pilot project. Nature 447:799–816.
8. Tramontano A (2005) Problem 4 Protein Structure Prediction. In: The ten most wanted solutions in protein bioinformatics. Chapman and Hall/CRC, Boca Raton, FL.
9. McIntosh AC (2006) Functional Information and Entropy in living systems. In: Brebbia CA, Suchrov LJ, Pascolo P (eds) Design and Nature III: Comparing Design in Nature with Science and Engineering. WIT Press, UK.
10. McIntosh AC (2009) Information and Entropy — Top-down or bottom-up development in living systems? Int. J. of Design & Nature and Ecodynamics 4(4):351–385.
11. Dawkins R (2003) The Information Challenge. Chapter 2.3 in: A Devil's Chaplain; Selected Essays by Richard Dawkins, Ed. Latha Menon, Phoenix.
12. Shannon CE (1948)The mathematical theory of communication. The Bell System Technical Journal 27: 379–423, 623–656.
13 Sanford JC (2005) Are random mutations good? In: Genetic Entropy and the Mystery of the Genome. Ivan Press, Lima NY, pp. 15–32.
14. Jackson SP (2002) Sensing and repairing DNA double strand breaks. Carcinogenesis 23(5):687–696, OUP.
15. de Laat WL, Jaspers NGJ, Hoeijmakers JHJ (1999) Molecular mechanism of nucleotide excision repair. Genes and Devel 13(7):768–785.
16. Freske S (1981) Creationist Misunderstanding, Misrepresentation, and Misuse of the Second Law of Thermodynamics. Creation Evol J 2(2): 8–16.
17. Nicolis G and Prigogine I (1989) Exploring Complexity: An Introduction. W.H. Freeman, New York.
18. Styer DF (2008) Entropy and Evolution. Am J Phys 76(11):1031–1033.
19. Gitt W (1989) Information: the third fundamental quantity. Siemens Review 56 (6):36–41.
20. Sewell, G (2000) A mathematician's view of evolution. Mathematical Intelligencer 22(4):5–7.
21. Thaxton CB, Bradley WL & Olsen RL (1992) Thermodynamics and the origin of life. In: The Mystery of Life's Origin. Lewis and Stanley, Dallas.
22. Horgan J (1991) In the beginning. Scientific American 264:116–125. Section concerning Stanley Miller, p. 117.
23. Nikolova EN, Kim E, Wise AA, O'Brien PJ, Andricioaei I, Al-Hashimi HM (2011) Transient Hoogsteen base pairs in canonical duplex DNA, Nature 470(7335): 498–502.

24. Trevors JT, Abel DL (2004) Chance and necessity do not explain the origin of life. Cell Biology International 28:729–739.
25. Abel DL (2009) The Capabilities of Chaos and Complexity. Int J Mol Sci 10: 247–291.
26. Yockey H (1992) Information Theory and Molecular Biology. Cambridge University Press, Cambridge.
27. Wicken JS (1987) Evolution, Thermodynamics and Information: Extending the Darwinian Program. Oxford University Press, Oxford.
28. Miller KR (2000) Finding Darwin's God: A Scientist's Search for Common Ground between God and Evolution ISBN 0–06–093049–7
29. Miller KR (2008) Only a Theory: Evolution and the Battle for America's Soul ISBN 978–0670018833
30. Meyer SC (2004) The origin of biological information and the higher taxonomic categories. Proc Biol Soc of Washington 117(2):213–239.
31. Abel DL & Trevors JT (2005) Three subsets of sequence complexity and their relevance to biolpolymeric information. Theor Biol & Med Mod 2:29.
32. Abel DL, (2009) The capabilities of chaos and complexity. Int J Mol Sci 10:247–291.