Every intelligent ghost must contain a machine

an information-processing machine

What is Life?

Erwin Schrödinger on the Chemical Basis of Life

(INCOMPLETE DRAFT: To be extended)

Aaron Sloman

School of Computer Science, University of Birmingham

Installed: 29 Feb 2016

Last updated: 1 Jun 2018 (minor corrections); 3 Sep 2018; 12 Dec 2018 (minor)

4 Mar 2016; 4 Apr 2016 (Added Note to chapter 6); 8 Jan 2018

This document is:

http://www.cs.bham.ac.uk/research/projects/cogaff/misc/schrodinger-life.html

Or goo.gl/6DHTJA

Also PDF

http://www.cs.bham.ac.uk/research/projects/cogaff/misc/schrodinger-life.pdf

---

Abstract

This is a collection of extracts from Schrödinger's 1944 book *What is life?* with some comments added by me, mainly trying to clarify what I think he is saying and why I think it is so important for anyone trying to understand how life as we know it is possible in this physical universe. What needs to be explained is not just how particular forms of life are possible, but how the mechanisms of physics and chemistry support the continual production of new forms of life. It is often claimed that the Darwin/Wallace theory of evolution by natural selection answers that question, but it doesn't answer this question: what provides the increasingly complex and varied collections of options for natural selection to choose from? My (partial) answer is: an increasingly complex and varied collection of construction kits, themselves products of evolution by natural selection. (Compare recursive structure-building functions in computing.)

What Schrödinger tried to do in this book could be described as attempting to characterise key features of the *Fundamental Construction Kit* (FCK) required to support the many types of *Derived Construction Kit* (DCK) required for biological evolution to have produced the many and varied forms of life we now have on our planet, as discussed in
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/construction-kits.html

A partial index of discussion notes is in
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/AREADME.html

This is part of the Turing-inspired Meta-Morphogenesis project:
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/meta-morphogenesis.html

What is Life?

Late in 2015, while working on a paper on evolution’s use of construction kits of many kinds Sloman(2016) I re-read Schrödinger’s little book,

Erwin Schrödinger, *What is life?,* CUP, Cambridge, 1944,

for the first time for many years, and was surprised to find that he had presented so many of the crucial ideas required to explain the possibility of biological evolution and the possibility of construction kits required for development and reproduction.

There are several problems. First the second law of thermodynamics states that complex systems will become increasingly disordered, whereas the opposite is true of individual living things and life in general, which becomes increasingly complex and ordered as a result of biological evolution. Part of the explanation is very familiar: since neither the earth, nor any individual organism on the earth is an isolated physical system, external sources of energy, including solar energy, heat energy from the earth’s core, and chemical energy can counter the tendency to increased entropy for some entities on the planet.

But that does not explain the origins or persistence of increasingly complex and detailed structures. that are required to preserve biological information during the development of an organism, and during reproductive processes across many generations.

The basic problem is how the genetic information is preserved both within an individual during the complexities of development and across individuals over generations. A secondary problem is how so much new complexity evolves over time. We’ll first focus on the answer Schrödinger [ES] gives to the question how it is possible for detailed specifications, encoded in complex molecules to survive across generations despite constant thermal buffetting and potentially disruptive influences during development and reproduction, despite the second law of thermodynamics and despite the fact that the fundamental mechanisms of quantum physics are statistical.

ES provides an answer by pointing out that although quantum theory implies that physical processes essentially involve statistical patterns of change and are therefore not deterministic, it also implies that there can be structures that are in stable states because, although they are capable of switching to new states, they are very unlikely to do so, unless affected by a sufficiently high energy impulse. That allows quantum mechanics to support not only indeterminism, but also long term determinism.

Moreover if a physical structure is in stable state S1 it may be capable of having another stable state S2, which may be at either a higher or a lower level energy state, or the same level as the original state.

The states are stable because the transition from one to the other, or from one of them to some other state requires a minimum energy packet to "get over a hump".

Many human-designed mechanisms use this feature, for example, a box with a liftable hinged lid that is stable when shut and also when opened and folded back, like some dustbin lids. In that case gravity provides the force that has to be overcome to move the lid from one stable state to another. Another familiar example is the commonly used lever and spring mechanism that forces a wall-mounted electric light switch to be in one or other of two stable positions, using the "toggle" design https://en.wikipedia.org/wiki/Light_switch#Toggle. Many engineering designs depend on multi-stability, including the combination of springs and levers that allow a heavy hinged item, such as a car boot (trunk) lid to be held safely (i.e. stably) in more than one position, i.e. when shut or when fully open. As it moves up or down springs are stretched or released, and when stretched they hold potential energy. When the lid is fully open gravity alone does not suffice to pull it down past the maximum energy peak.

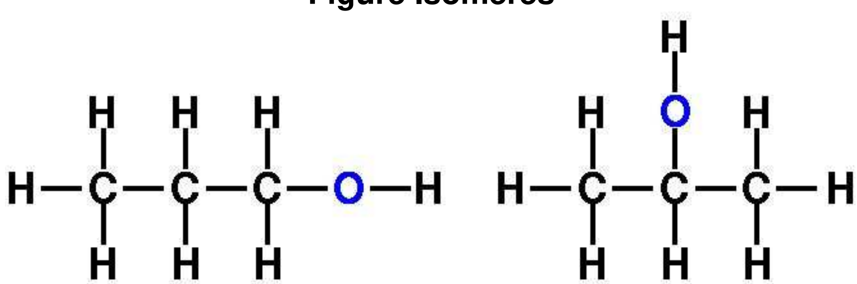
In some cases, instead of two or more fixed stable states a mechanism can allow collections of states each of which allows free motion, whereas the transition from one state to the other requires energy. An example is a flat tray that has grooves and circular hollows on it, and a marble that can move horizontally on the tray, while kept on the tray by the earth's gravitational pull. If the marble falls into one of the hollows or grooves it will be able to move around freely in the hollow or groove, but will not be able to jump to one of the other depressed parts of the tray unless the tray is given an extra strong jolt that communicates an impulse to the marble, making it jump out of the groove, and allowing it to move to other parts of the tray. How long a marble will resist being jolted out of a groove will depend on how deep the groove is, and how powerful the jolts are.

NOTE
This kind of multi-stable mechanism was used in a lecture by Lionel Penrose in the 1960s to demonstrate devices made of bits of wood, springs and hinges that could be shaken around on a tray, demonstrating some of the features of feeding, growth, and a-sexual reproduction. He called them "droguli". See
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/entropy-evolution.html#new-droguli

While trying to read Terence Deacon's 2011 book *Incomplete Nature: How Mind Emerged from Matter* I constantly had the impression that he had not understood these points, or had perhaps re-invented them with extraordinarily obscure terminology.

The above examples are partly analogous to the situation ES describes in which a molecule composed of several atoms may have two stable states which differ only in the location of one of the atoms.

Figure Isomeres



Two molecules with the same types of atoms connected differently
Each may be stable in the absence of a disruptive external influence

E.g. the two isomeres of propyl alcohol differ only in whether the oxygen atom (the blue "O" in the figure) is bound to the central carbon atom or an end carbon atom. Each state is stable because all their neighbouring states require higher energy. But if a sufficiently energetic impulse is received it can push the molecule over the energy "hump" and into the other stable state. This example is used in section 39 of the book, as the basis of several deep observations relevant to biological evolution.

In Chapter 7, ES discusses additional questions about the increasing complexity and variety of products of evolution and how that can be reconciled with what we know about the physical universe.

NOTE ADDED 4 Sep 2018
It seems that Schrödinger's ideas, expressed in this little book, still remain deeply influential/inspirational. E.g. see the discussion in Ogryzko(2008).

THE FORMAT OF THIS DOCUMENT

My comments from here on will be indented and italicised, as in this section, whereas quotations from the book are not indented and not italicised.

Many detailed technical sections of the text, and all mathematical sections, are omitted, in order to make this easy for a non-expert to read. I have also occasionally inserted paragraph breaks to help the reader.

After drawing attention to some biological phenomena and a background of physical laws, ES summarises puzzling biological phenomena that he wishes to show can be understood in the framework of Quantum mechanics but not previous physical theories (e.g. Newtonian mechanics augmented by statistical mechanics).

By the time the book was published (1944) there was already evidence that biological genetic information was stored and transmitted in extended chemical structures, and it was assumed that parts of those structures could specify particular inherited features. ES emphasises the fact that in some cases of biological inheritance, a particular unusual feature, which may be a product of a small portion of the genetic material can persist across several generations. He takes the "Habsburg lip" as an example. The reliable transition of a special feature across several reproductive episodes, each involving the development of a whole human from a fertilized egg cries out for explanation, as would preservation and replication of a triangular shape drawn in sand across Saharan sand dunes.

I think it is fair to say that the latter is impossible. ES tries to show what's special about genetic material that makes reproduction and preservation of detailed structure possible across even more complex disruptive processes than sand-storms. But he also tries to bring out why that is such a remarkable achievement and why it would have been impossible to explain on the basis of pre-quantum physics. For example, life as we know it would not have been possible in a universe composed of Newtonian point masses with mutual gravitational attraction. (I think Newton noticed this limitation of "Newtonian" mechanics, but I am not a Newton-scholar.)

NOTE
In another document I have tried to show the importance for science of discoveries and explanations of ***possibilities****, as opposed to discoveries and explanations of* ***laws****.*
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/explaining-possibility.html

---

ANNOTATED EXTRACTS FROM *WHAT IS LIFE?*

Chapter IV
THE QUANTUM-MECHANICAL EVIDENCE

32. Permanence unexplainable by classical physics

....
We are now seriously faced with the question: How can we, from the point of view of statistical physics, reconcile the facts that the gene structure seems to involve only a comparatively small number of atoms (of the order of 1,000 and possibly much less), and that value nevertheless it displays a most regular and lawful activity - with a durability or permanence that borders upon the miraculous?

ES uses the 'Habsburg Lip' as an example:

Fixing our attention on the portraits of a member of the family in the sixteenth century and of his descendant, living in the nineteenth, we may safely assume that the material gene structure, responsible for the abnormal feature, has been carried on from generation to generation through the centuries, faithfully reproduced at every one of the not very numerous cell divisions that lie between. Moreover, the number of atoms involved in the responsible gene structure is likely to be of the same order of magnitude as in the cases tested by X-rays. The gene has been kept at a temperature around 98°F during all that time. How are we to understand that it has remained unperturbed by the disordering tendency of the heat motion for centuries?
....
Of the existence, and sometimes very high stability, of these associations of atoms, chemistry had already acquired a widespread knowledge at the time. But the knowledge was purely empirical. The nature of a molecule was not understood - the strong mutual bond of the atoms which keeps a molecule in shape was a complete conundrum to everybody.
....
The evidence that two features, similar in appearance, are based on the same principle, is always precarious as long as the principle itself is unknown.

These extracts from the book indicate why such phenomena are problematic for current theories of physics, including thermodynamics, and chemistry. In all the statistical flux of matter in motion at temperatures of human bodies, how could something as minute as a molecular fragment specifying some biological feature, survive unchanged, even across many generations, despite all the copying required for reproduction and development? An outline answer follows:

33. Explicable by quantum theory
In this case it is supplied by quantum theory. In the light of present knowledge, the mechanism of heredity is closely related to, nay, founded on, the very basis of quantum theory.
....

The Heitler-London theory involves the most subtle and intricate conceptions of the latest development of quantum theory (called 'quantum mechanics' or 'wave mechanics').

....

34. Quantum theory--discrete states--quantum jumps

The great revelation of quantum theory was that features of discreteness were discovered in the Book of Nature, in a context in which anything other than continuity seemed to be absurd according to the views held until then.

....

For small-scale systems most of these or similar characteristics --we cannot enter into details-- change discontinuously. They are 'quantized', just as the energy is. The result is that a number of atomic nuclei, including their bodyguards of electrons, when they find themselves close to each other, forming 'a system', are unable by their very nature to adopt any arbitrary configuration we might think of. Their very nature leaves them only a very numerous but discrete series of 'states' to choose from. We usually call them levels or energy levels, because the energy is a very relevant part of the characteristic. But it must be understood that the complete description includes much more than just the energy. It is virtually correct to think of a state as meaning a definite configuration of all the corpuscles. The transition from one of these configurations to another is a quantum jump.

....

35. Molecules

Among the discrete set of states of a given selection of atoms there need not necessarily but there may be a lowest level, implying a close approach of the nuclei to each other. Atoms in such a state form a molecule. The point to stress here is, that the molecule will of necessity have a certain stability; the configuration cannot change, unless at least the energy difference, necessary to 'lift' it to the next higher level, is supplied from outside.

> ***NOTE:***
> *Some of the mathematical details in the book are skipped here. It turns out that there can be two possible states of a molecule with the same or similar energy levels, between which there are only transitions requiring much higher energy levels -- as in the toggle switch and car boot lid examples above. So either state could be equally stable at a given temperature. In other words, just because two states of molecule have the same energy it does not follow (in quantum physics) that it is easy to switch the molecule between those two states.*

38. First amendment

In offering these considerations as a theory of the stability of the molecule it has been tacitly assumed that the quantum jump which we called the 'lift' leads, if not to a complete disintegration, at least to an essentially different configuration of the same atoms -- an isomeric molecule, as the chemist would say, that is, a molecule composed of the same atoms in a different arrangement (in the application to biology it is going to represent a different 'allele' in the same 'locus' and the quantum jump will represent a mutation).

To allow of this interpretation two points must be amended in our story, which I purposely simplified to make it at all intelligible.

From the way I told it, it might be imagined that only in its very lowest state does our group of atoms form what we call a molecule and that already the next higher state is 'something else'. That is not so. Actually the lowest level is followed by a crowded series of levels which do not involve any appreciable change in the configuration as a whole, but only correspond to those small vibrations among the atoms which we have mentioned in §37.

....

So the first amendment is not very serious: we have to disregard the ’vibrational fine-structure’ of the level scheme. The term ’next higher level’ has to be understood as meaning the next level that corresponds to a relevant change of configuration.

39. Second amendment

The second amendment is far more difficult to explain, because it is concerned with certain vital, but rather complicated, features of the scheme of relevantly different levels.

The free passage between two of them may be obstructed, quite apart from the required energy supply; in fact, it may be obstructed even from the higher to the lower state.

....

It is known to the chemist that the same group of atoms can unite in more than one way to form a molecule. Such molecules are called isomeric (’consisting of the same parts’).

....

Isomerism is not an exception, it is the rule. The larger the molecule, the more isomeric alternatives are offered.

> *Isomerism is illustrated in the figure above, copied from the book. The two molecules have the same constituents, but because the oxygen atom has different locations in the two molecules they have very different physical and chemical properties. And neither state can easily be transformed into the other because the transition between the two states requires the molecule to pass through intermediate configurations which have a greater energy than either of them. ES writes:*

The remarkable fact is that both molecules are perfectly stable, both behave as though they were ’lowest states’. There are no spontaneous transitions from either state towards the other.

The reason is that the two configurations are not neighbouring configurations. The transition from one to the other can only take place over intermediate configurations which have a greater energy than either of them. To put it crudely, the oxygen has to be extracted from one position and has to be inserted into the other. There does not seem to be a way of doing that without passing through configurations of considerably higher energy.

....

Now we can give our ’second amendment’, which is that transitions of this ’isomeric’ kind are the only ones in which we shall be interested in our biological application. It was these we had in mind when explaining ’stability’ in §§35-37

....

Chapter V
DELBRÜCK’S MODEL DISCUSSED AND TESTED

40. The general picture of the hereditary substance

From these facts emerges a very simple answer to our question, namely: Are these structures, composed of comparatively few atoms, capable of withstanding for long periods the disturbing influence of heat motion to which the hereditary substance is continually exposed? We shall assume the structure of a gene to be that of a huge molecule, capable only of discontinuous change, which consists in a rearrangement of the atoms and leads to an isomeric molecule. The rearrangement may affect only a small region of the gene, and a vast number of different

rearrangements may be possible. The energy thresholds, separating the actual configuration from any possible isomeric ones, have to be big enough (compared with the average heat energy of an atom) to make the change-over a rare event. These rare events we shall identify with spontaneous mutations.
....

> ***Note**: this was published several years before the discovery of the "Double Helix" structure of DNA by Watson, Crick and their collaborators.*

41. The uniqueness of the picture
Was it absolutely essential for the biological question to dig up the deepest roots and found the picture on quantum mechanics? The conjecture that a gene is a molecule is today, I dare say, a commonplace. Few biologists, whether familiar with quantum theory or not, would disagree with it.
....
Why did I so strongly insist on the quantum-mechanical point of view, though I could not really make it clear in this little book and may well have bored many a reader?

Quantum mechanics is the first theoretical aspect which accounts from first principles for all kinds of aggregates of atoms actually encountered in Nature. The Heitler-London bondage is a unique, singular feature of the theory, not invented for the purpose of explaining the chemical bond. It comes in quite by itself, in a highly interesting and puzzling manner, being forced upon us by entirely different considerations.
.....
Consequently, we may safely assert that there is no alternative to the molecular explanation of the hereditary substance. The physical aspect leaves no other possibility to account for itself and of its permanence.
.....

42. Some traditional misconceptions

> **NOTE;**
> *This section discusses possible questions and confusions about similarities and differences between solids (crystalline and amorphous), liquids, gases, and which sorts of material can resist change of structure over long periods of time.*

43. Different states of matter
Now I would not go so far as to say that all these statements and distinctions are quite wrong. For practical purposes they are sometimes useful. But in the true aspect of the structure of matter the limits must be drawn in an entirely different way. The fundamental distinction is between the two lines of the following scheme of 'equations':

```
molecule = solid  = crystal.
gas      = liquid = amorphous.
```

We must explain these statements briefly. The so-called amorphous solids are either not really amorphous or not really solid. In 'amorphous' charcoal fibre the rudimentary structure of the graphite crystal has been disclosed by X-rays. So charcoal is a solid, but also crystalline. Where we find no crystalline structure we have to regard the thing as a liquid with very high 'viscosity' (internal friction). Such a substance discloses by the absence of a well-defined melting temperature and of a latent heat of melting that it is not a true solid.

.... further details omitted here ....

44. The distinction that really matters

....

The distinction that is really important in the structure of small matter is whether atoms are bound together by those Heitler-London forces or whether they are not. In a solid and in a molecule they all are. In a gas of single atoms (as e.g. mercury vapour) they are not. In a gas composed of molecules, only the atoms within every molecule are linked in this way.

45. The aperiodic solid

A small molecule might be called 'the germ of a solid'. Starting from such a small solid germ, there seem to be two different ways of building up larger and larger associations. One is the comparatively dull way of repeating the same structure in three directions again and again. That is the way followed in a growing crystal.

....

The other way is that of building up a more and more extended aggregate without the dull device of repetition. That is the case of the more and more complicated organic molecule in which every atom, and every group of atoms, plays an individual role, not entirely equivalent to that of many others (as is the case in a periodic structure). We might quite properly call that an aperiodic crystal or solid and express our hypothesis by saying: We believe a gene --or perhaps the whole chromosome fibre --to be an aperiodic solid.

....

NOTE:

In the next section ES shows that he understood the requirement for diversity in specifications expressed in the genetic code and pints out that this requirement can be met by his proposed molecular encoding mechanism, whose diversity of possible encodings increases exponentially with the length of the code. This was published a few years before Shannon (1948), but seems to have anticipated some of the ideas about requirements for transmission and storage of information vehicles.

*The diversity is a consequence of the aperiodicity mentioned in **45** above, which maximises the amount of genetic information that can be encoded in a structure of a given length composed of a sequence of items. Consider a linear structure that is made up of repetitions of a fixed structure as in 8 repetitions of a four length sequence of items, e.g. ABCD:*

ABCDABCDABCDABCDABCDABCDABCDABCD

*The only way to vary such a structure is to rearrange the order of the first four items, which determines everything else. So the number of possible strings of 32 atoms made of 8 repeated groups of 4 atoms is easily seen to be 4*3*2*1 = 24 (i.e. 4!). Moreover the number of possibilities is unchanged even if there are always 800, or 8000 repeated groups of 4.*

*On the other hand, if the fixed repetition requirement is removed and the four items can be in any order, and not necessarily each with the same frequency, then 32 four-way choices are available for assembling each sequence, providing a much larger total number of possible sequences 4**32 = 18446744073709551616.*

This implies that each genetic sequence of atoms, i.e. each genome(?), is a selection from an astronomically large set of possibilities. Of course, the number will be reduced if some sequences are excluded, as, for example, the sequence "TTT" is (somehow) excluded from

English words. But the set of English sentences expressed in N words grows rapidly even if it is less than full exponential growth, because not all sequences of sentence-components are sentences. (Something similar will be true of genome components.)

It was only later that the work of Crick, Franklin and Watson showed that evolution used not an alphabet of individual atoms, but a small "alphabet" of molecules, strung together in aperiodic sequences to specify genomes. It seems that Schrödinger understood the importance of aperiodicity some time before Shannon's work explained it.

46. The variety of contents compressed in the miniature code
It has often been asked how this tiny speck of material, nucleus of the fertilized egg, could contain an elaborate code-script involving all the future development of the organism.
....
Indeed, the number of atoms in such a structure need not be very large to produce an almost unlimited number of possible arrangements. For illustration, think of the Morse code. The two different signs of dot and dash in well-ordered groups of not more than four allow thirty different specifications. Now, if you allowed yourself the use of a third sign, in addition to dot and dash, and used groups of not more than ten, you could form 88,572 different 'letters'; with five signs and groups up to 25, the number is 372,529,029,846,191,405. **....**
What we wish to illustrate is simply that with the molecular picture of the gene it is no longer inconceivable that the miniature code should precisely correspond with a highly complicated and specified plan of development and should somehow contain the means to put it into operation.

NOTE:
Note that he does not say that the portions of code correspond with structural details or processes in the finished product, which would be a naive interpretation of what genetic code does. Corresponding to a "plan of development" could be almost as restrictive if every detail of the development process is specified in the plan. However if the plan includes conditional items (something like conditionals in a programming language) and loops then the detailed relationships between what is in the plan/code and the final product may be very complex and indirect and definitely not an isomorphism.

It seems that Schrödinger already knew by 1944 that biological reproduction did not constitute an "algorithmic" process that would always produce the same result (physically and behaviourally identical developing organisms) from the same genome. (Was that already common knowledge among biologists/biochemists?) See Sloman&Chappell (in progress).

47. Comparison with facts: degree of stability; discontinuity of mutations
....
Thus the threshold values the chemist encounters are of necessity precisely of the order of magnitude required to account for practically any degree of permanence the biologist may encounter; for we recall from §36 that thresholds varying within a range of about 1:2 will account for lifetimes ranging from a fraction of a second to tens of thousands of years.
....
These considerations make it conceivable that an isomeric change of configuration in some part of our molecule is, produced by a chance fluctuation of the vibrational energy, can actually be a sufficiently rare event to be interpreted as a spontaneous mutation. Thus we account, by the very principles of quantum mechanics, for the most amazing fact about mutations, the fact by which they first attracted de Vrie's attention, namely, that they are 'jumping' variations, no intermediate forms

occurring.

48. Stability of naturally selected genes

....

Granted that we have to account for the rare natural mutations by chance fluctuations of the heat motion, we must not be very much astonished that Nature has succeeded in making such a subtle choice of threshold values as is necessary to make mutation rare. For we have, earlier in these lectures, arrived at the conclusion that frequent mutations are detrimental to evolution. Individuals which, by mutation, acquire a gene configuration of insufficient stability, will have little chance of seeing their ’ultra-radical’, rapidly mutating descendancy survive long. The species will be freed of them and will thus collect stable genes by natural selection.

49. The sometimes lower stability of mutants

> ***NOTE:***
> *In this and the next section ES points out that whereas it is important for the majority of the genetic material to be highly stable, there must be some instability for mutations to occur. Moreover molecular instability can increase if temperature is increased. But if mutant genes are already unstable, a temperature increase should have a smaller effect on them than on more stable non-mutant genes. I’ve omitted most of the details.*

But, of course, as regards the mutants which occur in our breeding experiments and which we select, qua mutants, for studying their offspring, there is no reason to expect that they should all show that very high stability. For they have not yet been ’tried out’ --or, if they have, they have been ’rejected’ in the wild breeds --possibly for too high mutability. At any rate, we are not at all astonished to learn that actually some of these mutants do show a much higher mutability than the normal ’wild’ genes.

50. Temperature influences unstable genes less than stable ones

....

The time of expectation is diminished by raising the temperature, the mutability is increased. Now that can be tested and has been tested with the fly *Drosophila* in the range of temperature which the insects will stand. The result was, at first sight, surprising. The *low* mutability of wild genes was distinctly increased, but the comparatively *high* mutability occurring with some of the already mutated genes was not, or at any rate was much less, increased. That is just what we expect on comparing our two formulae.

....

> ***NOTE***
> *The predicted effects of Xrays are different from predictions for temperature increases. The effects of Xrays on the molecules they affect are more "explosive" (via production of ionised particles) and might be expected to affect normal and mutant genes in similar ways. Predicted effects are observed, helping to support the theory being presented. Details are omitted here.*

51. How x-rays produce mutation

....

52. Their efficiency does not depend on spontaneous mutability

....

53. Reversible mutations

NOTE
Some mutations are reversible. One might expect the energy for the original mutation and for the reverse mutation to be the same. But not if the mutated molecule and the original molecule have different energy levels, with a high energy barrier separating them. In that case the mutation from the higher energy molecule to the lower energy molecule might occur more frequently than the reverse mutation, since the reverse change requires a "bigger kick" to get over the hump. (My paraphrase.) Observed differences in rates of mutation in opposite directions are consistent with this theory.

Chapter VI: ORDER, DISORDER AND ENTROPY

54. A remarkable general conclusion from the model

Let me refer to the phrase on p. 62, in which I tried to explain that the molecular picture of the gene made it at least conceivable that the miniature code should be in one-to-one correspondence with a highly complicated and specified plan of development and should somehow contain the means of putting it into operation.

Very well then, but how does it do this? How are we going to turn ’conceivability’ into true understanding? Delbrück’s molecular model, in its complete generality, seems to contain no hint as to how the hereditary substance works, Indeed, I do not expect that any detailed information on this question is likely to come from physics in the near may future. The advance is proceeding and will, I am sure, continue to do so, from biochemistry under the guidance of physiology and genetics.

No detailed information about the functioning of the genetical mechanism can emerge from a description of its structure so general as has been given above. That is obvious. But, strangely enough, there is just one general conclusion to be obtained from it, and that, I confess, was my only motive for writing this book. From Delbruck’s general picture of the hereditary substance it emerges that living matter, while not eluding the ’laws of physics’ as established up to date, is likely to involve ’other laws of physics’ hitherto unknown, which, however, once they have been revealed, will form just as integral a part of this science as the former.

55. Order based on order

This is a rather subtle line of thought, open to misconception in more than one respect. All the remaining pages are concerned with making it clear. A preliminary insight, rough but not altogether erroneous, may be found in the following considerations:

It has been explained in chapter 1 that the laws of physics, as we know them, are statistical laws. They have a lot to do with the natural tendency of things to go over into disorder.

But, to reconcile the high durability of the hereditary substance with its minute size, we had to evade the tendency to disorder by ’inventing the molecule’, in fact, an unusually large molecule which has to be a masterpiece of highly differentiated order, safeguarded by the conjuring rod of quantum theory.

The laws of chance are not invalidated by this ’invention’, but their outcome is modified. The physicist is familiar with the fact that the classical laws of physics are modified by quantum theory, especially at low temperature.

There are many instances of this. Life seems to be one of them, a particularly striking one. Life seems to be orderly and lawful behaviour of matter, not based exclusively on its tendency to go over from order to disorder, but based partly on existing order that is kept up.

To the physicist --but only to him-- I could hope to make my view clearer by saying: The living organism seems to be a macroscopic system which in part of its behaviour approaches to that purely mechanical (as contrasted with thermodynamical) conduct to which all systems tend, as the temperature approaches absolute zero and the molecular disorder is removed.

The non-physicist finds it hard to believe that really the ordinary laws of physics, which he regards as the prototype of inviolable precision, should be based on the statistical tendency of matter to go over into disorder. I have given examples in Chapter 1. The general principle involved is the famous Second Law of Thermodynamics (entropy principle) and its equally famous statistical foundation.

In §§56-60 I will try to sketch the bearing of the entropy principle on the large-scale behaviour of a living organism -- forgetting at the moment all that is known about chromosomes, inheritance, and so on.

56. Living matter evades the decay to equilibrium

What is the characteristic feature of life? When is a piece of matter said to be alive? When it goes on 'doing something', moving, exchanging material with its environment, and so forth, and that for a much longer period than we would expect of an inanimate piece of matter to 'keep going' under similar circumstances. When a system that is not alive is isolated or placed in a uniform environment, all motion usually comes to a standstill very soon as a result of various kinds of friction; differences of electric or chemical potential are equalized, substances which tend to form a chemical compound do so, temperature becomes uniform by heat conduction.

After that the whole system fades away into a dead, inert lump of matter. A permanent state is reached, in which no observable events occur. The physicist calls this the state of thermodynamical equilibrium, or of 'maximum entropy'. Practically, a state of this kind is usually reached very rapidly.

....

These ultimate slow approaches to equilibrium could never be mistaken for life, and we may disregard them here. I have referred to them in order to clear myself of a charge of Inaccuracy.

57. It feeds on 'negative entropy'

It is by avoiding the rapid decay into the inert state of 'equilibrium' that an organism appears so enigmatic; so much so, that from the earliest times of human thought some special non-physical or supernatural force (vis viva, entelechy) was claimed to be operative in the organism, and in some quarters is still claimed. How does the living organism avoid decay? The obvious answer is: By eating, drinking, breathing and (in the case of plants) assimilating. The technical term is *metabolism*.

....

For a while in the past our curiosity was silenced by being told that we feed upon energy.

....

Needless to say, taken literally, this is just as absurd. For an adult organism the energy content is as stationary as the material content.

....

What then is that precious something contained in our food which keeps us from death? That is easily answered. Every process, event, happening -- call it what you will; in a word, everything that is going on in Nature means an increase of the entropy of the part of the world where it is going on. Thus a living organism continually increases its entropy -- or, as you may say, produces positive entropy -- and thus tends to approach the dangerous state of maximum entropy, which is of death. It can only keep aloof from it, i.e. alive, by continually drawing from its environment negative entropy -- which is something very positive as we shall immediately see. What an organism feeds upon is negative entropy. Or, to put it less paradoxically, the essential thing in metabolism is that the organism succeeds in freeing itself from all the entropy it cannot help producing while alive.

58. What is entropy?
Let me first emphasize that it is not a hazy concept or idea, but a measurable physical quantity just like of the length of a rod, the temperature at any point of a body, the heat of fusion of a given crystal or the specific heat of any given substance.

....

59. The statistical meaning of entropy
I have mentioned this technical definition simply in order to remove entropy from the atmosphere of hazy mystery that frequently veils it. Much more important for us here is the bearing on the statistical concept of order and disorder, a connection that was revealed by the investigations of Boltzmann and Gibbs in statistical physics.

....

An isolated system or a system in a uniform environment (which for the present consideration we do best to include as the part of the system we contemplate) increases its entropy and more or less rapidly approaches the inert state of maximum entropy. We now recognize this fundamental law of physics to be just the natural tendency of things to approach the chaotic state (the same tendency that the books of a library or the piles of papers and manuscripts on a writing desk display) unless we obviate it. (The analogue of irregular heat motion, in this case, is our handling those objects now and again without troubling to put them back in their proper places.)

60. Organization maintained by extracting 'order' from the environment
How would we express in terms of the statistical theory the marvellous faculty of a living organism, by which it delays the decay into thermodynamical equilibrium (death)? We said before: 'It feeds upon negative entropy', attracting, as it were, a stream of negative entropy upon itself, to compensate the entropy increase it produces by living and thus to maintain itself on a stationary and fairly low entropy level.

....

Thus the device by which an organism maintains itself stationary at a fairly high level of orderliness (= fairly low level of entropy) really consists continually sucking orderliness from its environment.

This conclusion is less paradoxical than it appears at first sight. Rather could it be blamed for triviality. Indeed, in the case of higher animals we know the kind of orderliness they feed upon well enough, viz. the extremely well-ordered state of matter in more or less complicated organic compounds, which serve them as foodstuffs. After utilizing it they return it in a very much degraded form -- not entirely degraded, however, for plants can still make use of it. (These, of course, have their most powerful supply of 'negative entropy' the sunlight.)

Sections 61--69 omitted

NOTE TO CHAPTER VI
(Included in 1955 edition)

The remarks on negative entropy have met with doubt and opposition from physicist colleagues. Let me say first, that if I had been catering for them alone I should have let the discussion turn on free energy instead. It is the more familiar notion in this context. But this highly technical term seemed linguistically too near to energy for making the average reader alive to the contrast between the two things. He is likely to take free as more or less an "epitheton ornans"[*] without much relevance, While actually the concept is a rather intricate one, whose relation to Boltzmann's order-disorder principle is less easy to trace than for entropy and "entropy taken with a negative sign", which by the way is not my invention. It happens to be precisely the thing on which Boltzmann's original argument turned.

[*] "Decorative epithet"

But F. Simon has very pertinently pointed out to me that my simple thermodynamical considerations cannot account for our having to feed on matter "in the extremely well ordered state of more or less complicated organic compounds" rather than on charcoal or diamond pulp. He is right. But to the lay reader I must explain, that a piece of un-burnt coal or diamond, together with the amount of oxygen needed for its combustion, is also in an extremely Well ordered state, as the physicist understands it. Witness to this: if you allow the reaction, the burning of the coal, to take place, a great amount of heat is produced. By giving it off to the surroundings, the system disposes of the very considerable entropy increase entailed by the reaction, and reaches a state in which it has, in point of fact, roughly the same entropy as before.

Yet we could not feed on the carbon dioxide that results from the reaction. And so Simon is quite right in pointing out to me, as he did, that actually the energy content of our food does matter; so my mocking at the menu cards that indicate it was out of place. Energy is needed to replace not only the mechanical energy of our bodily exertions, but also the heat we continually give off to the environment. And that we give off heat is not accidental, but essential. For this is precisely the manner in which we dispose of the surplus entropy we continually produce in our physical life process.

This seems to suggest that the higher temperature of the warm-blooded animal includes the advantage of enabling it to get rid of its entropy at a quicker rate, so that it can afford a more intense life process. I am not sure how much truth there is in this argument (for which I am responsible, not Simon). One may hold against it, that on the other hand many warm-blooders are protected against the rapid loss of heat by coats of fur or feathers. So the parallelism between body temperature and "intensity of life", which I believe to exist, may have to be accounted for more directly by van 't Hoff's law, mentioned at the end of Sect. 50[*]: the higher temperature itself speeds up the chemical reactions involved in living. (That it actually does, has been confirmed experimentally in species which take the temperature of the surrounding.)

[*] Not yet included in this online document.

Chapter VII: Is Life Based on the Laws of Physics?

61. New laws to be expected in the organism

("If a man never contradicts himself, the reason must be that he virtually never says anything at all." Miguel De Unamuno (Quoted from conversation))

What I wish to make clear in this last chapter is, in short, that from all we have learnt about the structure of living matter, we must be prepared to find it working in a manner that cannot be reduced to the ordinary laws of physics. And that not on the ground that there is any "new force" or what not, directing the behaviour of the single atoms within a living organism, but because the construction is different from anything we have yet tested in the physical laboratory.

> ***NOTE***
> *ES wrote this before the development, later in the 20th century, of computers running complex interacting virtual machines, whose construction could rightly be said to be different from anything physicists and engineers had previously built or tested in physical laboratories, and whose properties and behaviours cannot be described adequately in the language of the physical sciences, a point that is elaborated in a separate document:*
>
> > *http://www.cs.bham.ac.uk/research/projects/cogaff/misc/vm-functionalism.html*
> > *Virtual Machine Functionalism (VMF) -- The only form of functionalism worth taking seriously in Philosophy of Mind and theories of Consciousness.*
> >
> > *See also:*
> > *A. Sloman and R.L. Chrisley, (2003), Virtual machines and consciousness, Journal of Consciousness Studies, 10, 4-5, pp. 113--172,*
> > *http://www.cs.bham.ac.uk/research/projects/cogaff/03.html#200302*
>
> *I suspect that if ES had been able somehow to spend a week or a month talking to sophisticated AI researchers and software engineers in the 21st Century, about the variety of types of virtual machinery that can run and interact on a physical platform (or collection of connected physical platforms) he might well have said: "Yes that's the sort of thing I was struggling to identify in 1944". On the other hand, there there remain deep gaps between the spatial competences of current robots and the spatial competences of many intelligent animals, including crows, squirrels, octopuses, elephants, and pre-verbal human toddlers, e.g. as demonstrated in:*
> *http://www.cs.bham.ac.uk/research/projects/cogaff/movies/ijcai-17/small-pencil-vid.webm*
> *Moreover, despite the general belief that computers are very good at mathematics, it is not the case that AI systems show any ability to make the types of mathematical discovery in geometry and topology made by ancient mathematicians, including discoveries that go beyond Euclidean geometry, such as the discovery of the neusis construction, which makes it easy to trisect an arbitrary triangle, despite its impossibility using only Euclid's constructions. See*
> *http://www.cs.bham.ac.uk/research/projects/cogaff/misc/trisect.html*

To put it crudely, an engineer, familiar with heat engines only, will, after inspecting the construction of an electric motor, be prepared to find it working along principles which he does not yet understand. He finds the copper familiar to him in kettles used here in the form of long, wires wound in coils; the iron familiar to him in levers and bars and steam cylinders here filling the interior of those coils of copper wire. He will be convinced that it is the same copper and the same iron, subject to the same laws of Nature, and he is right in that. The difference in construction is enough to prepare him for an entirely different way of functioning. He will not suspect that an electric motor is driven by a ghost because it is set spinning by the turn of a switch, without boiler and steam.
....

To be expanded, showing how something with the apparent regularity and precision of clockwork mechanisms can continue operating for long periods of time in accordance with principles of Quantum mechanics but not in accordance with the kinds of reliable regularities found in statistical mechanics arising out of numerosity of individuals.

So, despite QM being famous for its "uncertainty principle" and for replacing the determinism of Newtonian mechanics with pervasive non-determinism, it is only QM, not Newtonian mechanics, that can explain the kind of persistence and replication of structure that is required for the existence of living things in all their many forms, including the ability to absorb, store, and use "negative entropy" either extracted from solar radiation (using photosynthesis) or by consuming and digesting parts of other organisms that have acquired such stores.

Schrödinger's little book provides a profound example of the importance for science of theories that attempt to answer the (Kantian) question "How is X possible?" Sloman (2014).

Note added 6 Mar 2016
It seems that recent work by Jeremy England referenced below, can be seen as extending the ideas in What is life? by using Quantum theory to explain how it is possible for some important precursors of life to come into existence on a lifeless planet. (Thanks to Aviv Keren for drawing my attention to this.) Some of the structures that might spontaneously form could be building blocks not only for some of the earliest forms of life (as described by Ganti (1971/2003)) but possibly also for some of the "construction-kits" and forms of scaffolding required for biological evolution. See
http://www.cs.bham.ac.uk/research/projects/cogaff/misc/construction-kits.html

TO BE CONTINUED

REFERENCES AND LINKS

- Erwin Schrödinger, 1944, *What is life?,* CUP, Cambridge.
- Natalie Wolchover, report on work by Jeremy England, "This Physicist Has A Groundbreaking Idea About Why Life Exists" in *Business Insider* Dec. 8, 2014, http://www.businessinsider.com/groundbreaking-idea-of-lifes-origin-2014-12
- Tibor Ganti, *The Principles of Life,* Eds. Eors Szathmary & James Griesemer, OUP, New York, 2003, Translation of the 1971 Hungarian edition, (Review by Korthof: http://wasdarwinwrong.com/korthof66.htm)
- V.V. Ogryzko, 2008, Erwin Schroedinger, Francis Crick and epigenetic stability, *Biology Direct*, 3, 15,
  http://doi.org/10.1186/1745-6150-3-15

  Includes:
  "A shift from the signal transduction paradigm to the epigenetic one might be useful for the study of many other protein modifications and even of interactions between macromolecules."

- Claude Shannon, 1948, A mathematical theory of communication, July and October, 1948 *Bell System Technical Journal,* 27, pp. 379--423 and 623--656,
- http://www.cs.bham.ac.uk/research/projects/cogaff/crp/chap2.html
  Aaron Sloman (1978)
  'What are the Aims of Science?' Chapter 2 of *The Computer Revolution in Philosophy: Philosophy, Science and Models of Mind*
  Whole book: http://www.cs.bham.ac.uk/research/projects/cogaff/crp/
  including Chapter 2.
- http://www.cs.bham.ac.uk/research/projects/cogaff/misc/explaining-possibility.html
  Aaron Sloman (2014), Using construction kits to explain possibilities Online Discussion paper.
- http://www.cs.bham.ac.uk/research/projects/cogaff/misc/construction-kits.html
  Aaron Sloman (2016--Still under development)
  The scientific/metaphysical explanatory role of construction kits:
  fundamental and derived kits, concrete, abstract and hybrid kits, meta-construction kits.
  Online incomplete discussion paper. A version frozen in 2016 was published as an invited book chapter, as follows:
- Aaron Sloman, (2017) Construction Kits for Biological Evolution, in *The Incomputable: Journeys Beyond the Turing Barrier,* pp 237--292, Eds. S. Barry Cooper and Mariya I. Soskova,
  http://www.springer.com/gb/book/9783319436678
- Aaron Sloman and Jackie Chappell (work in progress)
  The Meta-Configured Genome
  http://www.cs.bham.ac.uk/research/projects/cogaff/misc/meta-configured-genome.html

---

Maintained by Aaron Sloman
School of Computer Science
The University of Birmingham