# Towards a Theory of Life

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**Abstract.** In this paper, I set out the contributions made by some European biologists, as well as other more heterodox ones, to the recent development of theoretical thinking in biology. Theoretical biology is a relatively new discipline when compared with theoretical physics, in part because the formal languages of logic and computing which it uses have only emerged recently. Finally, I suggest that in order to build a theory of life we need to combine a cell theory based on a proper description of the laws that map the genotype in the phenotype and vice versa with the laws of evolution. Only then will we be able to properly explain the transformation and complexity of living things.

## 1 Introduction

A biologist presenting their ideas on logic and computing at a conference of experts in computing - computing with membranes to be precise - is surprising for two reasons: firstly, because it reflects the intellectual openness of the computer scientists who invited me, and then secondly because I think they sense, like me, that there is a very close relationship between biology and computing. Hence I believe that my audaciousness in presenting my ideas in such a special forum is justified.

The purpose of this paper is to describe my own path to discovering what I can now put forward as an early thesis statement: that logic and computing are the natural abstract languages of biology, in the same way that calculus was in its day for physics. I do not mean that other formal languages are not appropriate for biology, but rather that computing is the most appropriate one. I have reached this conclusion by way of some fairly tortuous thinking which I am going to set out in this paper, a paper which, in a nutshell, is a condensed version of my recent book "The Calculus of Life" [1]. The logic in its development has a certain historical chronology involving three periods. The first relates to the relevance which particular biologists, who can in some way be considered recent pioneers of theoretical biology, have had for me. Although admittedly, they are just some of the scientists and intellectuals who have influenced me. The second period coincides with my search for ways of approaching biology


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from logic and computing. Computing is a recent science, as is modern logic, even though it precedes computing. Some of the reasons why it has been so difficult to develop theoretical biology, in the same way as we have theoretical physics that is almost as old as physics itself, are internal to biology, mainly the complexity of its many objects of study. However, here I will look at the late development of languages, namely logic and computing, which are appropriate for biology. Biology has been waiting for them, and when we have begun to apply them, biological theorising has soared to levels of explanatory depth of biological entities which were barely imaginable beforehand. Finally, the third period is my own thinking in the field of new biology, the field of systems. This modern biology is the one that Goethe would have dreamed of, and probably other later vitalist authors too. Theoretical biology is arranged around the biology of (computable) systems. We can model and compare biological phenomena and we are on track to improve this even more. This modern biology means that theoretical biology is not a purely speculative field that is excessively conceptual and abstract and unconnected with biologists empiricist interests.

## 2 Biology

There is a fine tradition of recent theoretical thought in biology which, in some ways, has been buried by the subsequent emergence of biology popularisation literature, mainly about biological evolution, which has been promoted by British or American authors such as Gould and Dawkins to mention just two great icons in the field. They are authors, scientists themselves, who also wrote and thought about biology. I consider them as important forerunners for the establishment of theoretical biology. The list is skewed by my own interests but their names are well known: Jacob and Monod, pioneers of molecular biology, von Bertalanffy, a pioneer of the systemic conception of entities including biological ones, and Waddington, a pioneer of theoretical biology. There are other authors worthy of attention who go back even further than the four I have just mentioned and whose logical-mathematical training and willingness to address biology as a whole were very significant. Here I am talking about Woodger, Turing, Rosen and von Neumann. Although I briefly discuss the work of these latter four, in my book I focus on the four I mentioned previously, probably because they are scientists involved in the research of life.

Monod poses a key problem in biology, one which hovers over its entire history. It is the confrontation or the relative weight that contingency and chance have had in the evolution of life compared with necessity. In fact, contemporary biology is strongly influenced by the idea that new biological developments of any kind appear by chance and are selected. Necessity has a teleological aftertaste to the extent that if you examine the tree of life and the time when these fresh developments have emerged, you get the impression that the most recent ones are more complex than the oldest ones. Put in another way, the evolution of life is an evolution in complexity. However, we do not have much experience with which to test this. The ideal experiment would be to see the dynamics of life on other planets where it has emerged.

Jacob is important for his theories about reductionism, particularly in its ontological variant. As a pioneer in molecular biology he confers full powers on genes to map the phenotype. He does not deny that properties not written in the genes may emerge, but he claims that these properties appear because the genes are there. Genes are the basic units that are transmitted from generation to generation and it is their products which, in broad interaction between them and with the environment, make it possible to create that entire functional superstructure which we call a living being.

von Bertalanffy is the father of the general systems theory. If anyone could be credited with the idea that the whole is greater than the sum of its parts, that person would be von Bertalanffy. von Bertalanffy is the most theoretical of all my favourite theoretical biologists. Living organisms are systemic conglomerates at all their levels. Cells, multicellular organisms, populations, ecosystems; all these hierarchies of biological organisation are systems formed by the most basic unit components from which properties emerge. von Bertalanffys systems contrast with Jacobs ontological reductionism. Yet that is biology, in which there is always a vigorous debate between the analytical-reductionist and synthetic-systemic traditions.

Finally, Waddington is the great conceptual father of modern theoretical biology. We owe the concept of epigenetics to him, and like few others he was prescient in seeing that the big problem of biology lies in the discovery and integration of the laws governing the relationship between genotypes and phenotypes. Biology requires the development of a phenotype theory which combines the laws that map the genotype in the phenotype and the phenotype in the genotype. Although Waddington, and anyone at this time, recognises the enormous contribution that genetics has made to verifying the tree of life proposed by Darwin, i.e. confirmation of the unit and the genealogical relationship between all living beings, it is still an insufficient and gene-centric contribution to the origin and transformation of living beings. For Waddington, I would repeat, we need an evolutionary theory of the phenotype.

## 3 Logic and Computing

Modern logic was born with Frege and Boole and its history is recent when we consider the Aristotelian origins of traditional logic, which is as old as reasoning in the West. I mention the youth of modern logic to stress that the science of computing has largely drawn on these authors, particularly Boole, for the advent of computing which, obviously, is even younger than modern logic. What does computing have that makes it so familiar to biology and means I venture to claim that it is a very appropriate formal language for it? Consider the extraordinary analogy of hardware (machinery) and software (algorithm) in computing with cellular machinery, proteins or the phenotype as biological hardware and DNA or genes as biological software, program or algorithm. As far as biology is concerned, the twin concepts of hardware/software (machinery/program) have permeated it to such an extent that much of the deep reasoning underlying modern biology, particularly in molecular biology, uses concepts drawn from computing. Hence we can say that DNA - at least, because there may be other informational levels - is an informational program or algorithm run at the cellular level by the protein machinery. The relationship between computing and biology is deeper than this, because if we admit the algorithmic nature of DNA then we can assess whether, for example, it is feasible to measure its complexity or whether the cell is a Turing machine.

However, I would now like to stress one aspect of computing which in my view is fundamental to biology; the simulation of biological phenomena. In my book, I use two examples, which can now be seen as historical, and which explore and contrast the properties of living beings. They are the cellular automaton called 'Life' by the mathematician Conway and 'Algorithmic Chemistry' by Fontana and Buss.

'Life' is a cellular automaton playing with the fundamental property of life; its ability to persist. In fact, a cell of the grid (which would be the equivalent of an organic cell) is defined as living or dead by the status of its eight neighbours. It starts from an initial set of live or active cells which are arranged in a certain way in the grid. Rules are applied to them in order to assess in successive rounds (generations) what the map of living cells will be, continuing the process for as long as they exist. Though the rules are simple, indeed disdainfully simple, they show properties on the grid that are reminiscent of the behaviour of living beings such as cooperation, competition, multiplication or the indefinite survival of some of the structures formed by these cells, etc. The rules are as follows: (a) if two neighbouring cells are alive, the reference cell maintains its status: dead if it was dead and alive if it was alive; (b) if there are three live neighbours, the reference cell will be alive regardless of whether it was alive or dead before applying the rule; and (c) if the number of neighbouring live cells is zero, one, four, five, six, seven or eight, the reference cell will die after applying the rule.

'Life' is an example of life dynamics under deterministic rules that make up a closed evolution. The dynamic is the same whenever we begin with the same number of cells, including their location, as well as the same starting grid size (the environment). However, in spite of this and as noted above the simulation captures many properties of living entities.

Another computational approach to biological phenomena which intrigued me at the time is Fontana and Busss 'Algorithmic Chemistry'. It is essentially a reactor consisting of a set of initial objects which are structures that follow the rules of lambda calculus, well known in computational theory. The total set of objects remains constant and in each cycle or generation they are allowed to interact or collide with each other to reconfigure the population in terms of composition. A general observation in all the experiments conducted in these reactors was the invariable appearance after a reasonably high number of cycles of new objects, usually much more complex than any of the initial ones, which exhibited properties typical of biological entities such as self-maintenance and multiplication. They also observed emergent properties. Indeed, they identified the emergence of new complex objects due to the joining together of others which, in turn, already had a degree of complexity and exhibited new properties with respect to those presented by the combined objects. These behaviours emulated the hierarchical organisation of biological entities where, for example, cells which exhibit specific properties are grouped into tissues or organs that collectively present other properties.

These computational experiments by Fontana and Buss show behaviour typical of the evolutionary dynamics of open systems. Although the rules or axioms are defined, the interactions between the objects are not, and instead are random, and the simulation itself allows the incorporation of mutations (random alteration of objects in the reactor at any time during the experiment). However, the amazing thing was the systematic emergence and persistence of complex structures with emergent properties and organisational hierarchy in spite of the contingency introduced by the chance factor of the random combination of the objects and mutations. It would be something like a kind of necessity inherent in the dynamics of the living entities which evolved towards greater complexity.

## 4 Cell and Evolution

The development of a theory of life would involve a suitable combination of two sets of sub-theories which unfortunately have been unevenly developed. They are the theories of the cell and of evolution. It is almost a platitude now to say that the fundamental unit of life is the cell, and this is a key finding of biology which has been well accepted for centuries. Indeed, it predates evolutionary theory itself, which has only been consolidated after much time and effort. Yet taking the cell as the basic unit of life is not the same as saying that we thoroughly grasp all the processes that occur within it. Molecular biology has been the science that has taken the most important steps in examining the structure and function of cellular components in depth. However, we still need to draw up a catalogue of the laws that govern it. To a great extent, and going back once more to the twin concepts of (genetic) information and (metabolic) cellular machinery, the phenotype of a cell is far from fully understood on the basis of its primary genetic information (genotype). In fact, the laws of transformation that enable us to infer the phenotype (or mapping) from the informational genotype as well as possible additional epigenetic laws are the big problem of modern biology. Nevertheless, we should not think that as a result we have not made great strides. Quite the reverse is the case. We are in a very sweet spot in research into the cell as a fundamental unit in which we are close to learning as never before about its collective behaviour (as a whole) based on real-time knowledge of all its fundamental components and processes. In the history of biology, ridicule has been heaped on vitalist authors, some of them distinguished biologists, who refused to accept that the essence of life - for example the essence of a cell - can be captured by studying its parts. This vitalist tradition began with Goethe and continued with Bergson and Driesch. Their intention would probably be not so much resorting to a non-physical principle in which to site the essence of living things, but rather the unavailability of methodological and conceptual procedures to address living entities as a whole. These authors would be reconciled with modern biology if, as Mayr says, we showed them that relationships between the parts of an entity, which we can now measure, are as important as the parts themselves. It would be like Goethes dream come true.

As I noted above, modern evolutionary theory confirms without a shadow of a doubt the union of all organisms in their evolution from the moment that life appeared on Earth. Nevertheless, deeper understanding of this transformation and the gradual emergence of more complex forms calls for the addition of thorough knowledge of the laws of genotype-phenotype transformation of the cell. The combination of the two sub-theories would provide a unified theory of life.

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