What is life?

Raphael Falk

Department of Genetics

and

The Program of History and Philosophy of Science

The Hebrew University of Jerusalem

> I wish to devote this talk to two friends who were active participants of this Society for the Origin of Life: the late Shneor Lifson, with whom I loved to discuss these problems of the meaning of life, and whose points of views were often diametrically different from mine, and my colleague Uzi Ritte, whose intimate knowledge and involvement in the theory of evolution as an experience in nature always attracted me.

Sooner or later, every student of biology is faced with the problem of **what is life**. But not only biologists wonder, physicists too: We are all familiar with Erwin Schrödinger's booklet "What Is Life?" who in the 1940s was faced with the molecularization of the concept of the gene as attempted by Max Delbrück, characterizing genes in terms of "atomic associations" (*Atomverbände*). Schrödinger came to the conclusion that these must be "aperiodic crystasl", crystals that transgressed their accepted defining property of ordered organization.

Here, in referring to the oxymoron *aperiodic crystal*, Schrödinger already clearly exposed the problem of defining Life: it must be bounded by the laws of physics, yet it supervenes them. In other words, although the laws of physics govern life as much as everything else in the world, life cannot be reduced to the laws of physics. So, what is it that makes life a unique phenomenon and what made it so successful? Well, Schrödinger said it: aperiodic crystals, a level of organization of matter beyond the reductive laws of elementary physics and chemistry.

No wonder that Schrödinger's booklet attracted many physicists to engage in problems of life and indeed in trying to show that the phenomenon of life could, after all, be reduced to the laws of physics. As a matter of fact, Schrödinger like Niels Bohr hoped to discover in the study of living organisms new laws of physics:

> We must not be discouraged by the difficulty of interpreting life by the ordinary laws of physics. … We must be prepared to find a new type of physical law prevailing in it. Or are we to term it a non-physical, not to say a super-physical law? (Schrödinger, 1944 (1962), p 80-81)

Indeed, molecular biology, starting with the formulation of the Watson - Crick Model of the structural organization of the DNA molecule, provided the foundation for the most basic functions of life – namely, storage of information, its self-replication, and its mutagenesis. It triumphed up to the 1970s not only the success of the Galilean *methodology* of *reductionism*, but also the success of *conceptual reductionism*, as it had been painstakingly elaborated in physics over the two preceding centuries.

Crick's "Sequence Hypothesis" and the "Central Dogma" of 1958, of the unidirectional transfer of information from polynucleotide sequences to polypeptide sequences, was the climax if this *reductionist conception of Life*. From then on, following developments from within molecular biology itself, it became increasingly clear that the reductionist notion of physics would not suffice to accommodate new notions like the operon, intron, alternative splicing, overlapping reading sequences, and more.

Thus, it was from within bottom-up reductionist molecular biology that the need for a top-down conception for the study of living systems resurfaced or emerged. It became clear that it was the organization of matter and function that provided life its unique meaning. Biological, and especially molecular-biological research, became more and more top-down *conceptualized*, in terms of systems' organization, while not abandoning reductionist, bottom-up *methodologies*.

This brings me back to the eternal problem of a differential definition of life.

It is, of course, possible to dismiss the problem of 'what is life', by arguing that the category of "life" is a human invention, rather than that of a natural kind. Some would say that living things have merely a (Wittgenstinian) family resemblance, namely that different forms of life might share various characteristic properties, but each individual property in the cluster could be missing in some members of the family.

Still, an important insight of Lamarck, and I think also of Buffon, was their characterization of the difference between physics and biology: the crucial feature, they pointed out, was that biological systems are physical systems constrained by their *history*, while physical systems—for the most part—have no history.

> To say of something that it is water is [normally] to say nothing at all about its history. … On the other hand, to say of something that it is a zygote is to tell us something of its history. (Ruse, 1973)

Or, to be more contemporary, life as we know it today is the *uninterrupted*, ongoing sequel of improbable physical processes of complex molecular structures that draw on their environment for material, energy, and entropy.

As put by Mark Bedau in a recent paper that is about to appear in the journal *Astrobiology*, there are two possible approaches to defining life: The Cartesian approach of defining (presumably *a priori*) necessary and sufficient properties for the phenomenon of life wherever we looks for it in the universe; and the Aristotelian approach of defining life as we experience it.

The Cartesian approach seeks necessary and sufficient conditions for being an individual living organism, whereas the Aristotelian approach considers life in the whole context in which it actually exists; it looks at the characteristic phenomena involving actual life, and seeks the deepest and most unified explanation for those phenomena. According to the Cartesian approach life wherever we claim it in the universe has the same elements; according to the Aristotelian conception, life in different sites and at different times in the universe may vary profoundly from life-as-we-know-it here. The question remains, however, whether there are any properties that although they do not define life as a universal phenomenon, at least describe it.

Years ago, in the early 1980s, I argued with Yeshayahu Leibowitz whether genetics can explain development (Falk, 1985). He denied this, and used to quote Kant that it is "absurd for human beings…to hope that there may yet arise a Newton who could make conceivable even so much as the production of a blade of grass according to natural laws which no intention has ordered." Leibowitz emphasized that a causal explanation in the sciences is only an efficient or moving force, embedded in the *past* of phenomena, whereas development or differentiation of organisms, he insisted, indicated dependence on final causes, teleological causes, directed by *future* phenomena, thus belonging to the realm of the Aristotelian speculative philosophy:

> We have to differentiate between the living world and the inanimate world, not from the perspective of their essence but by considering the categories of their perception in our thought. In other words, our problem is not "living versus inanimate" but of "biology versus physics." (Leibowitz, 1983, p. 116)

Leibowitz, the Believer scientist, clearly defined the phenomenon of life as belonging into the *meta*physical sphere. I tried to get help from the theory of Darwinian evolution that essentially all life that we conceive today converges to one single root, the outcome of innumerable processes in time and space that gradually evolved as sequences of (random) trial and (selective) error over the millennia. Once the a priori improbable sequence of events, which we conceive (post factum) as life, started it was only a problem of more mutations and their selection that was needed to (eventually) produce both the leaf of the grass and the intellect of Newton. I argued that the development of a blade of grass was not due to a teleological cause, but the result of a long Darwinian process of efficient forces of selection of random mutations. In other words, an essential element in the evolution of life depended on the evolution of a Program, a *system* of physico-chemical reactions interdependent and coordinated in time and space. Such a program would allow the repeated reinvention of the system, if in due curse the system contained also the machinery that took care of the program. Thus the system that survived contained elements that maintain it, as a distinct confined system in time and space.

As Bedau suggests such a program must have three necessary but also sufficient elements to function as a living system. Even the simplest biological organisms are very complicated chemical systems. In his words:

> The phenomena of life might be difficult to delimit precisely, but it certainly includes life's characteristic hallmarks. … The Program-Metabolism-Container (PMC) model, … construes minimal chemical life as a functionally integrated triad of chemical systems …
>
> Minimal chemical life is defined operationally as the simplest chemical systems that deserve to be considered to be alive. (Bedau, in press)

And in Barnes and Dupré's words:

> According to theorists of the early origins of life, molecules evolved in the primeval soup. In particular, they evolved methods of reproducing themselves and went to grow in size and complexity as molecular systems, until finally we were inclined to call them living things … [G]enomes are molecules, and probably the distant descendants of the RNA molecules central to the self-replicating molecular systems that evolved in the primeval soup. (Barnes & Dupré, 2008, p. 126)

Between the world of molecules, in which self-replicating systems somehow come into existence and perhaps evolve, and the world of microbes, a crucial event is generally reckoned to have occurred, the "Darwinian transition" involving the confinement of chemical systems and the emergence as bounded living objects or cells. A precondition of the Darwinian transition was the development of the cell membrane, the structure that allowed the metabolic processes of organisms to occur largely insulated from interactions with whatever lay outside the cell membrane (Barnes & Dupré, 2008, p. 130). This is again, Bedau's Program-Metabolism-Container model, or as I prefer to change the sequence, the Program-Container-Metabolism version.

This Aristotelian definition of life, accepts that life is a unique sequence of events in the history of the world, not because other sequences that we may have conceived as life could not have occurred – they most probable did occur and may occur even today – but only because this sequence is the one that happened to survive the "struggle for existence."

As Martin Gardner said: "Strange events permit themselves the luxury of occurring" (Gardner, 1957, p. 307). Considering the time span and the number of celestial bodies, the strangest sequences of events may have occurred, and with the input of natural selection may have occurred more than once along their unique and specific way. And as stressed by Ronald Fisher:

> The "one chance in a million" will undoubtedly occur, with no less and no more than its appropriate frequency, however surprised we may be that it should occur to *us*. (R. A. Fisher, 1953, pp. 13-14)

We look at one of these (im)possible sequences of events *a posteriori*. And as Ruma Falk has shown experimentally, we always view events that occurred to *us* as more surprising as similar events that occurred to *others*.

> I find my own story more surprising than I find yours. I think that my story is more surprising than you think it is. (Falk, 1989, 479)

This is probably also why it is so difficult for us to accept the evolution of life, our specific kind of life that occurred to us on Earth.

At the end of his paper Bedau asks: *Why is life so puzzling?* His answer is:

> [B]ecause people give the question a Cartesian rather than Aristotelian interpretation. The Cartesian seeks necessary and sufficient conditions for being an individual living organism, independent of any particular environment. The Aristotelian seeks the most plausible, comprehensive, and unified underlying explanation for the characteristic phenomena associated with life. (Bedau, in press)

Barnes, B., & Dupré, J. (2008). *Genomes and what to make of them*. Chicago: University of Chicago Press.

Bedau, M. (in press). An Aristotelian account of minimal chemical life. *Astrobiology*.

Falk, Raphael (1985). Can genetics explain development? In E. Ullman-Margalit (Ed.), *The Prism of Science* (pp. 165-180). New Jersey: Humanities Press.

Falk, Ruma. (1989). Judgment of coincidences: Mine versus yours. *American Journal of Psychology, 102*(4), 477-495.

Fisher, R. A. (1953). *The design of experiments* (6th ed.). Edinburgh: Oliver & Boyd.

Gardner, M. (1957). *Fads and fallacies in the name of science*. New York: Dover.

Leibowitz, Y. 1983. Does genetics explain development: From Kant to the genetic code. (Hebrew) *Mada, 27*(3), 116-120.

Ruse, M. (1973). *The philosophy of biology*. London: Hutchinson University Library.

Schrödinger, E. (1944 (1962)). *What is life? The physical aspect of the living cell*. Cambridge: At the University Press.