THE THREE FACES OF LIFE
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Abstract

Contrary to the cherished beliefs of many physicists and other unreconstructed materialists, there's a lot more to life than mere matter. What distinguishes life from non-life is how the matter is organized. This paper argues that by retreating from a resolutely Newtonian view of life and returning to the Aristotelian notion of causal categories, we open up new avenues of approach to understanding the interconnections among early life forms, artificial life in machines and possible types of extraterrestrial life.

1. The Why of Life

According to Caesar, all Gaul was divided into three parts. And so it is too when it comes to the study of life, where we find that the deepest questions seem to be parceled out among three seemingly distinct categories. The first, of course, is just the wet, squishy, carbon-based type of life we're familiar with here on Earth. Into this Category I fall all the usual origin-of-life (ORI) questions involving the way life got its start on this planet. Category II is of much more recent vintage, centering less upon how life got its start and more upon the even deeper question made famous by the title of Erwin Schrödinger's book, *What is Life?* In this category we find the current work on artificial life (AL), which seeks to answer Schrödinger by constructing life based on patterns of information in silicon and electricity instead of in carbon and water, or possibly on new combinations of the standard chemicals constituting life here on Earth. Finally, we come to close encounters with life of the third kind: extraterrestrial life forms (ET). Here in Category III reside all the puzzles involving the possible nature of life forms evolving under environmental conditions radically different (or, perhaps, indistinguishable) from those found here on Earth. Superficially, these categories appear to be pretty much disconnected. Or at least that's the impression one gets from a reading of the scientific research literature. In the spirit of the Ars Electronica Symposium on Artificial Life, I'll argue in this paper that not only are these categories inextricably intertwined, but that the adoption of a more functionally oriented view of life opens up the possibility for a productive interchange of ideas among research groups pursuing work in the different categories.

Just about the first, thing every journalist learns is that a good story answers the following questions: Who? What? When? Where? Why? How? Applying this tried and true principle the story of life' it's not too hard to see that these interrogatives can be apportioned out among our Categories I—III as follows:

• Origin of Life. How? Studies of the origin of life on Earth tend to focus almost exclusively on questions beginning with "How." Occasionally, as with various extraterrestrial theories of the origin of life' "Where" enters the picture too. But' by and large' ORI studies center on the construction of various scenarios for how life got going on Earth four billion years or so ago. This issue is, of course, intimately bound up with the so-called "origins problem," we ask what features of modern life forms would be preserved were we able to "rewind the tape" and start the process all over again. We'll return to this question later.

• Artificial Life: What? The key issue around which most AL studies revolve is Schrödinger's famous question: What is life? Put more specifically, we ask if a suitably organized pattern of information in a machine can ever constitute a genuine living organism? So the operative word here is "What."

• Extraterrestrial Life: Who? Where? When? "Where are they?" This was Enrico Fermi's famous retort to the claim that the universe must be filled with ET's. Studies over the intervening half century or so have centered mostly on where to look' what to look for and when will we find something (someone?).

The most striking aspect of this list of journalistic interrogatives is the singular absence of "Why." So if Schrödinger's question governed studies of life in the 20th century' I'd like to predict that 21st-century studies of life will be driven by the question' "Why is life?" Let me take a page or two to explain.

2. From Newton to Aristotle

The basic goal of modeling, mathematical or otherwise, is to answer the question "Why?" According to Newton (a physicist), the corresponding "Because" is given in terms of local interactions involving material particles and unexplainable forces. Aristotle (a biologist) had a quite different way of saying "Because."

In Aristotle's view, the "Why" of things can be described in terms of three basic entities: (i) the material substance comprising physical objects' (ii) the abstract or geometric forms that objects can assume, and (iii) the processes of change by which either the substance or the form may be transformed. Thus, Aristotle's "Because" results in four disjoint and inequivalent causal categories which, taken together, provide a complete answer to "Why" the world is as it is. These causal categories are:

• Material cause — things are as they are because of the matter of which they are composed;
• Efficient cause — things are as they are because of the energy that went into making them as they are;
• Formal cause — things are as they are because of the plan according to which they were built;
• Final cause — things are as they are because of the desire or will of someone to have things take their current state.

Note that in the above scheme of things, material cause corresponds to substance, with efficient cause relating to processes for changing the substance. Similarly, formal cause explains the abstract or geometric form of an entity, with final cause describing how one changes the form. This scheme explains why there are four basic causes in the Aristotelian view of the world, and not three or five or 3,469.

In the epistemology of Aristotle, all things can be explained by invoking the four basic causes, each cause illuminating a different fundamental aspect of the system at hand. We can also interpret these inequivalent causal categories by thinking of each category as being concerned with the manipulation of "something" as indicated in Table 1.

Table 1. Aristotelian Causal Categories and Manipulations

Cause	Property Manipulated
Material	Physical Matter
Efficient	Energy
Formal	Information
Final	Desire; Will

Interestingly enough, both the Newtonian and Aristotelian explanatory schemes talk about the same thing: a material substance and the process by which this substance can change.

However, in the Aristotelian picture substance is not enough; one also needs the idea of form and some kind of dynamic by which one form can be transformed into another. This latter idea is totally absent from the Newtonian picture. In partial compensation, the Newtonian setup offers a mathematical apparatus by which we can encompass both the particles (material cause) and the forces (efficient cause) that constitute the heart of the Newtonian modeling paradigm. The Aristotelian picture provides no mathematical machinery, only a verbal description of the causes. It's instructive to examine this dichotomy in a bit more detail in order to get a feel for what must be done to extend the Newtonian formalism to accommodate the additional Aristotelian causes.

Newton's Second Law is usually written as the differential equation x(t) = F(t), $x(0) = x_0$ where x(t) is the state of the system of particles at time t, the quantity F represents the unexplained external forces, and x° is the initial state of the system. For our purposes, it's more convenient to write this relationship in integrated form as x(t) =x [integral sign] t0 [phi] (s)ds where [phi] (s) plan [integral sign] s0 F(r)dr.

Now we can ask the question: Why is the system in the state x(t) at time t? Newton can give only two answers:
1) The system is in the state x(t) at time t because it was in the state x0 at time t plan 0 (material cause);
2) The system is in the state x(t) at time t because the operator [integral sign] A0 plan … plan transformed the initial state to the state at time t (efficient cause).

Thus, the Newtonian framework has neither the need nor the room to accommodate the additional Aristotelian categories of formal and final causation. Some would argue, myself included, that this fact more than any other accounts for the banishment of formal and especially final cause from polite scientific conversation for the better part of three centuries. There is just no room to fit them in to the classical Newtonian framework.

In actuality, even the most die-hard Newtonian ultimately came to recognize, albeit implicitly, that the missing causal categories would somehow have to be grafted on to the classical setup. In particle systems, the role of formal cause is usually assigned to various parameters specifying important constants in the situation. So things like as particle masses, gravitational constants, electric charges and so on serve to characterize the "plan" of the system. It's through the specification of such parameters, and their incorporation into the mathematical framework, that formal cause enters by the backdoor into the Newtonian scheme of things. But what about final cause? How does Newton deal with the idea of desire or will? The simple answer is that he doesn't.

When reading Aristotle's account of the causal categories, one is struck by the great significance he attaches to the notion of final cause. In fact, for Aristotle it seems that final cause was just a little more equal than any of the other categories, and he reserved his greatest respect and kindest words for what would today be termed (by Newtonians) "teleology." For the kinds of problems that concerned Newton, it appears reasonable to omit final causation from consideration since it's different to imagine non-living, material particles having any particular kind of will, volition, or consciousness. Thus, Newton and his successors had no need to invoke any of the ideas associated with final cause, notions like goals, plans, will, or even self-reference, in their analyses of physical processes.

From this point of view, it's rather easy to understand why the mathematical machinery they employed seemed perfectly adequate to the task at hand, even though it contained no natural way to account for final cause and dealt with even formal cause in a rather ad hoc manner. Unfortunately for the biologist, economist, and psychologist, Newton's prescriptions were too successful in answering questions in physics, chemistry, and engineering, leading to a gradual emergence of the view that it's a breach of scientific etiquette, if not downright unscientific, to allow anything even smacking faintly of final causation to enter into polite scientific discourse. In other words, if you can't use the methods that work in physics, then you're not doing science. And using the methods of physics means working within the Newtonian paradigm.

Newton's world naturally sees organisms as being just special kinds of material objects; in short, biology is a subset of physics. Aristotle's *Weltanschauung,* on the other hand, argues for just the opposite view, implying that the physics of particles and forces is just a special kind of biology. In other words, the Aristotelian world is one in which the Newtonian framework is just a special case of a broader-based paradigm suitable for characterizing life. Aristotle's problem was that he had no mathematical formalism at his disposal with which to describe his causal theory. But mathematical modeling has developed considerably in the two thousand years since Aristotle. And one of its fruits has been the development of a formal framework that helps in putting several questions from ORI, AL and ET onto a common footing. This framework is called a metabolism-repair system (M,R)-system, whose details are outlined in the papers[1—6]. Since these results are a bit too involved to go into here, let it suffice to say that the (M,R)-systems represent an abstract version of a living cell. Now let me indicate how the combination of Aristotelian causation and the (M,R)-setup help illuminate some of the key issues arising in ORI, AL and ET.

3. The Hen or the Egg?

Almost all competing theories of the origin of life involve a scenario in which either the first living thing was a metabolizer that later acquired the ability to replicate' or is a replicator that then assumed metabolic functions. Thus the question: Which came first, the hen or the egg? While the current flavor of the month in the ORI business seems to be a replicator-first theory involving an evolution of life from self-catalytic RNA, the (M,R)-framework strongly suggests otherwise. On purely logical grounds' quite independent of physical substrates like nucleotide bases, amino acid chains and all the other paraphernalia of earthly life, it's very difficult to see how to start with an abstract replicator like RNA and make metabolic activity emerge from replication. There does not appear to be any straightforward way to begin with the process of replication and use "natural" mathematical operations on sets and maps to create a metabolizer. Part of the difficulty comes from the fact that the repair component of the cell acts as an intermediary between replication and metabolism, and it's just far simpler to see how to make this operation come about from something rather than having to emerge from nothing. And since replication involves no actual production of something new, but only the copying of something old, there's just not enough raw material to work with to get the job done. So if you believe in the (M,R) framework, then you'll also believe that the time is ripe for metabolism-first theories of ORI to begin making a comeback. Turning now to Aristotle and his causes, the very nature of the ORI problem seems to call for an explanation of life on Earth by material causation. And, in fact, the distinguishing characteristic separating the competing theories — self-rep RNA, hypercycles, clay, iron — is the kind of material substance they postulate that the first organism was made of. But the (M,R)-framework is one grounded in formal and final cause, not material and efficient. In particular, by thinking in these alternative causal categories we are able to pin down the elusive notion of final cause: it is simply the cell's purpose or, in biological terms, its design metabolism. Let's briefly consider how these notions enter into the origins problem discussed earlier.

4. Life by Design

One of the cornerstones of the scientific method is the notion of a repeatable experiment: results obtained by one researcher at one lab should be replicable by other researchers working under similar circumstances. This idea of repeatability enters as a central ingredient in the process of validating scientific claims and establishing today's conventional wisdoms on what Nature is and isn't doing. Clearly, the replicability requirement poses severe difficulties for researchers in areas like the origin of life, cosmology, evolution and, in general, every area in which there is a single set of observations available and in which the system cannot be reset to the beginning and allowed to start over again. This is the so-called "origins problem" The question, of course' is what can be done to surmount it?

One line of attack on the question in origin-of-life studies is to ask: Suppose we could rewind the tape and let the system start over again. Are there any properties of existing life forms that we would expect to see reappear in the new world of "Earth II"? In other words, are there certain features of organisms that are "generic," and that can be expected wherever life exists? Or is our form of life special in every possible way? Recently, Walter Fontana and Leo Buss have examined this issue using tools from mathematical logic and evolutionary theory"). They conclude that there are indeed such generic properties, things such as self-maintaining organizations (self-repair), entities that catalyze their own replication and hierarchical organization of living entities. In a certain definite sense, these results relate to what we might call the logic of life. So in the Aristotelian scheme of things, they have to do with formal cause. But what about artificial life forms built from the usual materials — carbon, hydrogen, oxygen and all the rest — of everyday life?

It's difficult to read a newspaper science page nowadays without encountering some story about how the wizards of molecular biology are concocting new genetic patterns to cure diseases, increase crop harvests or eliminate pests. What's happening here, of course, is that the genetic engineers are constructing strands of RNA/DNA of a type never before seen in any naturally occurring organism. Let me consider just one example.

In 1992, Gerald Joyce and Amber Beaudry, researchers at the Scripps Institute in California, succeeded in coaxing a biological molecule to evolve artificially, doing in a few weeks what Nature might take millennia to perform[12]. Starting with a population consisting of trillions of molecular variants of a strand of RNA, Joyce and Beaudry evolved an RNA enzyme that would snip strands of DNA 100 times more efficiently than the starting molecule. In short, these researchers achieved what might be called, evolution by "unnatural selection." Earlier work had shown how to mimic two of the three ingredients needed for Darwinian evolution: selection and amplification. But the crucial ingredient added in the Scripps experiment was that it allowed molecules to also mutate randomly. So in our Aristotelian categorization, we can explain the work of Joyce and Beaudry by appeal to material causation — but of a type never before seen in any natural organism.

Before closing the all-too-brief discussion of life by design, let me mention in passing the extensive amount of work being done under the general rubric "robotics." As anyone who saw the film "Star Wars" is well aware, robots are another way to study life by designing objects that capture the behavioral and cognitive features of natural organisms — including human beings! Now let me shift the venue from real life to real artificial life.

5. Life in Silico

In summer 1991 Tom Ray, a plant biologist in Delaware, created a computer program that reproduces — undergoes spontaneous genetic changes, passes them on to its offspring and evolves new species whose interactions mimic those of real biological evolution and ecology — all without human guidance or intervention[9]. The significance of Ray's program was that it was the first logical demonstration of the validity of the Darwinian theory of evolution. This is exactly the goal of the artificial lifers: to show that the logical structure of life is completely independent of material cause. True or not, just as with work on ORI, in AL too there is something to be gained by thinking in terms of other causal categories.

For instance, Darwinian theory implies that the environment in which an organism develops will strongly influence the physical form and function of the organism. This is a material cause explanation for why the vast majority of living things on Earth are shaped like cylinders with appendages. But suppose we have something like Ray's electronic organisms that evolve within the cozy confines of a computer's memory banks. Thinking in terms of material cause, we can ask: what is the shape of such an electronic "bug"? And what would such an organism see when it looks at its "environment"? And in what way does the bug have to adapt to such an environment? And so on and so forth. The point is that we are led to ask a quite different set of questions than those that naturally come to mind in the original setting of formal cause.

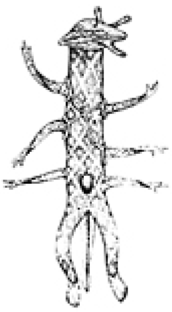
In another direction, we can point to the work initiated by Dutch biologist Aristid Lindenmayer on artificial plants. Using a small number of simple rules involving branching directions, leaf types and the like, Lindenmayer and his colleagues have created a stunning array of plant-like objects that bear a striking similarity to the kinds of flowers and trees found naturally here on Earth[10]. But of course, these "electronic plants" have never graced anyone's backyard garden or appeared on the menu in any haute cuisine restaurant. They are the epitome of what we can call artificial plants. Before leaving the matter of life in silicon, let me add that by taking a collection of abstract cells of the type in the (M,R)-framework and connecting them into a network, it's possible to construct an electronic ecology similar to that produced in Ray's computer. Some suggestions about how this might be done are given in the papers[1—6]. One result that comes out of such an exercise is the purely logical fact that immortality is flatly impossible. In other words, not all genetic lines can perpetuate themselves indefinitely. This is explanation by formal cause. It's reasonable to suppose that additional light will be shed on this phenomenon by looking at it from the vantage point of material causation. But this is a matter for future research. For much further discussion of this point, the reader should consult the "bible" of artificial life[8].

6. Who Goes There?

From a physical life point of view, certainly the most central question surrounding the existence of ET is: What do "they" look like? In other words, what kind of physico-chemical structure is an ET likely to have? This, of course, is basically a problem of material and efficient cause. And for the spectrum of possible answers, it's hard to do better than to consult the "hard" science fiction literature.

The creature depicted in Figure 1 below shows an artist's depiction of a Cygnan, a race of alien beings that threatens the Earth in Donald Moffitt's classic science-fiction novel *The Jupiter Theft*. The Cygnan is from a race of creatures the evolved on the satellite of a gas giant planet orbiting a binary star system. He (she? it?) is about 11/2 meters tall, with six limbs that can be used as either arms or legs' and a long, three-petaled tail that folds to conceal the sexual organs. The slender, tubular body is built on a cartilaginous skeleton, with the brain located between the upper pair of limbs at the top of the spinal cord. The three eyes are placed on stalks in an equilateral triangle around a broad' flexible mouth. The Cygnan has a harsh, rasping plate in the mouth, and a spiked, tubular tongue. It has a well-integrated nervous system, with much faster synaptic reflexes than those of a human being. Cygnan speech is musical, consisting of chords produced by multiple larynx es, and depends on absolute pitch. The language is incredibly rich and varied; it has more than a million phonemes, and each word is made up of several phonemes.

So here we have a well worked-out example of an ET that differs radically from earthly organisms in almost every way that counts (unfortunately for the humans in Moffitt's story). But if we consider formal cause, the science-fiction literature offers up even stranger possibilities.



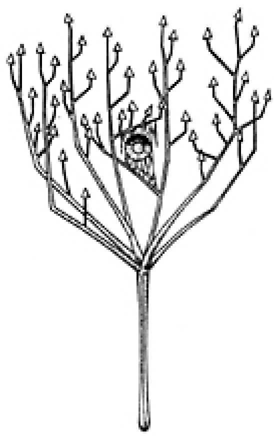


Figure 2 shows the Cryer, a creature from Joseph Green's book *Conscience Interplanetary*. The Cryer is an independently functioning unit of a planet-wide silicon-based plant intelligence inhabiting the planet Crystal, which has an atmosphere of 18 percent oxygen, the rest being nitrogen and hydrogen. Life on Crystal is based on silicon, with a high percentage of metallic elements. The Cryer resembles a two-meter-high bush with a crystal-and-metal trunk and branches, with small, sharp glass leaves. The trunk contains silicon memory units, powered by a low-voltage solar storage battery and connected by fine silver wires. About six feet up the Cryer's trunk is an organic air-vibration membrane that enables the Cryer to speak with human beings. It is a broad, saucer-shaped leaf held in place by stretched wires to provide a vibrating diaphragm. A magnetic field generated in silver wire coils hanging on either side of the speaker causes it to vibrate and produce sound.

The planet-wide intelligence consists of thousands of smaller units like the Cryer, connected by an underground nervous system of fine silver wire. Each unit has a specialized function, some storing electricity generated by sunlight, some extracting silver for constructing the nervous system, some providing memory storage, and some acting as sensor units. The overall intelligence is able to perceive temperature, motion, position, electrical potential and vibrations through its member units.

Cygnans and Cryers are, of course, just thought experiments. Many more are reported in the imaginative volume[7]. By considering the almost infinite range of possible life forms, and by examining the ET problem from all four of the Aristotelian causal perspectives, we can hope to get some feel for what may turn up on our radio telescopes or in our back yards one of these days. And, in fact, as the paper[1] points out, the metabolism-repair systems form what in mathematics is termed a "category" of objects. Therefore, each and every member of this category corresponds to a different biology, opening up the possibility of studying exobiologies by examining the mathematical structures and constraints imposed by these different objects in the category.

7. That's Life!

This paper has argued that to understand the difference between the living and the dead, it's not sufficient to concentrate just on the material aspects of living things. By adopting a less Newtonian and a more Aristotelian view of the problem, one is led to give equal time to explanations of life in terms of other causal categories besides the material. In particular, we have shown that there is much to be gained (and nothing to be lost but prejudices) by considering the other forms of life beyond those commonly encountered here on Planet Three. The overall conclusion that emerges is that there are significant synergies possible between earth life, artificial life in machines and extraterrestrial life "out there," and that researchers in each area can benefit from paying careful attention to work by those in the other categories. To paraphrase a famous remark about war and generals, life is just too important to be left to the biologists.

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