Natural Philosophy: Developmental Systems in the Thermodynamic Perspective

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Herein I give an outline of Natural Philosophy as I see it at the beginning of the Twenty First Century. It exemplifies a modern Aristotelian in approach.

ONTOLOGY

The ontology of Natural Philosophy is constructed from knowledge produced by the natural sciences (Durali, 1996). My perspective on it (Salthe, 1993, 2001b, 2002b, 2004a, 2004b) relates to the point of view of the 'Unity of the Sciences' movement, but without that movement's intent to reduce all understanding to physical dynamics. This ontology can most efficiently be presented as a 'specification hierarchy', as follows, in set theoretic format:

{physical dynamics **{**chemical recognition and bonding **{**biological form and cognition **{**sociopolitical organization **{**linguistic cognition**}}}}}**

interpreted as **{**lower integrative level **{**higher integrative level **}}**

A specification hierarchy (Salthe, 1991, 1993, 2000b, 2002a, 2005b, 2006b) has the form of a tree branching from its root (here in physical dynamics). However, the hierarchy shown here traces only one path through the branches, in the interest of illuminating human existence in the light of scientific knowledge -- which I take to be the goal of Natural Philosophy. Each bracket marks a new realm of being. Moving to the right in the illustrated hierarchy, a bracket signifies a boundary, in the sense that the knowledge involved at any integrative level to the left of the bracket is insufficient to understand the higher level shown to its right in the hierarchy. Thus, biology cannot be fully understood using only chemical concepts and language, even though it could said that biology is fundamentally a special kind of chemistry (as is indeed shown in the above hierarchy), and so is afforded by the chemical integrative level. Biology is based in the chemistry of macromolecules, wherein historically marked differences between molecules can have functionally distinct significance, something unknown in abiotic chemistry.

All levels lower than it provide various material causes (Salthe, 2006a) for processes and events at any integrative level, which could not exist without them. At the same time each level generates formal and final causes for the lower integrative levels that it constrains locally, so that, moving to the left in the hierarchy, the 'point' of a bracket suggests a 'top-down' organizing relationship -- contextualization, control, regulation. Thus it is said that each level 'integrates' the levels below it, harnessing them in its interests. Integration involves imposing limits, but not usually to the point of full determination. As an example of integration, physical diffusion is integrated into biology by means of the forms involved in the organization of circulatory systems.

From an informational perspective, we may note that, in the set theoretical format of the specification hierarchy, the higher levels also imply the existence of the lower levels. Referring to the material systems being modeled, this is material implication, or conceptual subordination. That is, biology implies or conceptually subordinates the existence of chemistry, which in turn implies the existence of physical processes. This format allows as well tentative logical representations of evolutionary discoveries by way of a process of generalizing. Thus, we may postulate, for example:

{ teleomaty **{** teleonomy **{** teleology **}}}** (implied e.g., by Mayr, 1985)

or

{ physical tendency **{** function **{** purpose **}}}** (see Salthe, Website for further details)

Following directly upon this, interpretations currently foreign to the ideology of science would find here a representation of finality, with the higher level phenomenon being not only implicit in the lower levels, but immanent prior to its emergence.

Fixing our attention upon the lowest level, we find that with each added bracket (marking a subclass in the formalism) more constraints are imposed upon possible physical dynamics, limiting them to ever more restricted trajectories. And so a tornado, for example, is actually freer to behave in any which way within its reach than is an organism. But it has many fewer possible kinds of distinct behaviors to access. If examined only at the physical level, the new information imposed at each emergent level restricts the primordial physical dynamics to fewer and fewer options, yet each level initiates some new degrees of freedom as well. These would have been only potential, and could not have been realized except fleetingly, in unconstrained lower integrative levels. So, while old degrees of freedom are squeezed ever more tightly as we ascend the hierarchy, new ones are instituted with each added integrative level. For example, with linguistic cognition, certain patterns of sound waves (spoken, say, while purchasing a loaf of bread) can have quite different consequences for the configuration of surrounding physical forces than other patterns (spoken, say, while robbing the shop), even if both statements are mediated by the same amount of energy dissipation.

Furthermore, with each level, new opportunities for individuation arise, so that, as we ascend the hierarchy, there can be increasingly more functional types and individuals with each higher distinction. Individuality may well exist in the purely physical realm of quarks and photons too, but as far as we know there is no consequence of that level of individuation in the rest of the world. Thus, the specification hierarchy marks the increasing effects of history with each higher integrative level. So a kind of protein can have more functionally different variants than can any kind of chemical species (which would be restricted to racemates), and there can be more functionally different kinds of chemical species than there can be, for example, kinds of electrons. As well, there can be more functionally different organisms in a population than there can be, say, kinds of fluid vortices -- and more functionally different linguistic statements than functionally different individuals in a biological population. As we ascend the hierarchy, the world is an increasingly more particular place. We could represent this concept with:

{ bound energy **{** types **{** individual tokens **{** proper names **}}}}**

which could also be re-represented as:

{ relatively vague **{{{** increasingly more definite **}}}}**

The development of embryos exemplifies and demonstrates the natural generation of this form admirably.

CHANGE

As already realized by Aristotle, the above format, which was first sketched as a synchronic form by Plato, implicitly points to a pattern of change, which we can represent as:

{ primordial germ --> **{{{** increasingly more definite embodiment **}}}}**

It may be that Aristotle was here building upon the earlier work of Anaximander, who visualized a developmental pattern moving from (what we would now call) vague to crisp (John McCrone, personal communication). It is in this diachronic interpretation that, when viewing this structure as an implication hierarchy, we would find the higher integrative levels functioning as final causes of the lower levels. In any case, the developmental interpretation of the specification hierarchy encourages us to reinterpret our initial specification hierarchy above as a result of the history of our Universe, in this way:

{ Big Bang expansion -> **{** matter and gravitation -> **{** material masses and the Second Law of thermodynamics -> **{{{** increasing refinement of energy gradient dissipation through diversification of types of dissipative structures **}}}}}}**

In more detail, the accelerated expansion of the Universe prevents its continuation in the presumably primordial condition of energy equilibrium (Nicolis, 1986). The resulting cooling of the Universe manifests in the precipitation of some of its energy as matter, which then activates gravitation. Gravitating matter forms various clumps leading to the formation of galaxies. Thus the expansion mediates an increase in order along with an increase in the possibilities for disorder (Frautschi, 1982). As an ‘equal and opposite’ reaction to the accumulation of material energy gradients, the Second Law of thermodynamics emerges as the tendency of the Universe to regain thermodynamic equilibrium (Salthe, 2004b). Biological and cultural evolution on Earth (and possibly on other relatively temperate planets) elaborates a great variety of dissipative structures, each devoted to consuming different energy gradients. Entropy production is a necessary byproduct of these activities because all work is relatively poorly energy efficient (Odum, 1983), and the faster or harder work is done the proportionally more entropy is produced relative to the energy used in work while dissipating the gradient.

In this perspective we see the embodiment of ever more information as the universe continues to expand (Frautschi, 1982), with each of us participating in its elaboration as we individuate.

There are two general kinds of change -- evolution and development (Salthe, 1993; Durali, 1996). Based in biological usage, I have defined them for general use thus:

evolution (or individuation) = the irreversible accumulation of the results of historical accident.

development = predictable directional change

If we examine changes accruing to collections of any kind of objects or systems over a significant period of time, we would find that some changes characterize all or most of the examples, while many seem to be unprecedented. These latter produce the individuation of the objects, while the predictable changes can be taken to be the constitutive changes of the kind of object or system involved. Such predictable changes, if they occur sequentially, would constitute a system’s canonical developmental sequence of changes (its developmental stages), while the accumulation of unique changes in each object or system mark its individuation, or evolution.

With data from biology, ecology and fluid dynamics, using the strategy of confirmation I have found (Salthe, 1993) a pattern of thermodynamic and informational changes that appears to be robust for individuals or systems across these discourses. And so I have suggested that these make up a sequence of canonical developmental stages for dissipative structures in general, which could be labeled as follows:

{ immature stage **{** maturity **{** senescence **}}**

which stages would be characterized (Salthe, 1989) as follows:

IMMATURITY:

(1) Relatively simple in form, and in some respects relatively small in size as well.

(2) Rapid increase in elaboration of form (rapid development).

(3) Relatively large energy throughput per unit mass (intrinsic or mass specific throughput).

(4) Rapid increase in gross energy throughput.

(5) The system has significant dynamical stability to same scale perturbations.

MATURITY: (temporarily stabilized only in the higher integrative levels)

(1) Relatively complicated in form, and in some regards larger in size than in the immature stage. The system has accumulated large amounts of information, which is

serving as constraints internally, and as sources of a variety of potential configurations that could be used to protect against environmental perturbations.

(2) The system's form has become definitive for its kind.

(3) Intrinsic energy throughput has decreased and continues decreasing

(4) Gross energy throughput is large and increasing slowly.

(5) The system is able to effectively deploy significant amounts of energy to ward off and heal insults from its environment.

SENESCENCE:

(1) Increasingly more complicated in form. The system keeps taking on new informational constraints despite being already definitive (i.e., functional) for its kind. This leads to information overload, resulting in delays in adaptive responses. This process takes place even in those systems where growth has stopped (a simple example would be pockmarks from asteroid impacts on the moon).

(2) We see a continuing increase in internal complication.

(3) Intrinsic energy throughput is gradually dropping lower and lower.

(4) Gross energy throughput has leveled off, and, in cases where growth stops, begins to decline.

(5) Stability to perturbations increasingly declines, setting the system up for recycling. This is a result in part of increasing stereotypical responses, providing less flexibility in the face of perturbations.

THE MAXIMUM ENTROPY PRODUCTION UNDERSTANDING

Inspired by experiments in fluid dynamics like the Bénard Instability, it was proposed that natural locales and systems will operate so as to maximize the rate of dissipation of available energy gradients (e.g., Schneider and Kay, 1994; Swenson, 1997; Salthe and Fuhrman, 2005). This is a local nonequilibrium understanding of the Second Law of thermodynamics, which operates globally in isolated systems. (The isolated system in Nature is taken to be the Universe itself.) Several ecologists have corroborated this with ecological data (Schneider and Sagan, 2005), and now a related principle has been formally established as the 'maximum entropy production principle' (MEP) in physics, to the effect that: a system that is free to access numerous configurations will spontaneously reorganize in such a way as to maximize its entropy production (Dewar, 2005). This, of course, would necessarily entail maximizing the rates of energy gradient dissipation as well.

Energy gradient dissipation is not identical with entropy production from that gradient. The rate of gradient dissipation can be estimated from the rate of energy flowing through a system that is consuming it (that system's 'power'). Some of that energy (the 'exergy') will be utilized for the work of maintaining or growing the system that is consuming the gradient. The rest will be lost as 'heat energy' and often various waste products, which are energy gradients that cannot be utilized by the system. Both of these are losses to the system in the form of the 'entropy' produced during work. With respect to work, there is plentiful evidence that natural systems will tend to maximize their gross energy flowthrough, which is used in work -- this being the 'maximum power principle' (Odum and Pinkerton, 1955; Jørgensen, 2001)). Other things being equal, this principle maps closely to MEP because work in natural systems is rarely as efficient as 50% and is usually much worse (Odum, 1983). Moreover, as work is accomplished more rapidly, its energy efficiency drops even lower (Salthe, 2003b). So, there is almost always a close correlation in natural systems between the maximum power principle and the maximum entropy production principle.

We have seen in the previous section above, however, that each individual system will experience a decline in mass specific, or intrinsic, power as it ages (Prigogine, 1955; Zotin,1972; Aoki, 1995). This is known as the 'minimum entropy production principle'. At the same time, however, most systems do continue to increase (but at decelerating rates) their gross energy throughput, which is what is expressed in the maximum power principle. That is to say that the minimum entropy production principle is not generally in conflict with the maximum entropy production principle. There could be situations where these principles would conflict, but they would be rare in natural systems. So, the general principle is MEP, with the minimum production principle applying to the per unit mass entropy production of individual systems as they senesce.

One can identify three classes of energy gradient dissipation, keyed to the size of the energy gradient (its distance from thermodynamic equilibrium) and its rate of dissipation. The lowest gradients would always be associated with gradual dissipation, as with diffusion, or gradual erosion or decay. These processes directly produce heat energy -- the undirected vibrational energy of molecules -- which is 'entropy' in its basic, definitive physical sense. At the other extreme we can have very steep energy gradients, very far from thermodynamic equilibrium. When these dissipate all at once we have an explosion. Examples would be bombs, the release of energy from large pressure gradients during volcanic eruptions, the sparking of electromagnetic energy -- and we can even find an example in the cylinders of gasoline engines. In this category there is a large production of primary heat energy, as well as sound wave energy and light, but there can also be the production of fragments of items that could not withstand the force of the explosion. As small gradients these will subsequently experience a slow diffusive dissipation. There can also be, in more organized situations, the movement of pushed objects, as in the cylinders of an engine, and so we can see that these explosive dissipations might represent work.

Work is a tricky concept, in that it is not a primary physical concept, like spacetime, matter, and fields (Salthe, 2005a). In its basic physical sense it is the lifting of objects against gravity. However, like information, it is generally associated with a system which has some kind of 'interest' in it. A tornado could be considered to do work when it smashes houses and moves them to new locations only if we were to consider it to be a bonafide 'agent' with 'interests'. Of course, in physical / engineering discourse the interested agent is always implicitly some human agency.

Given that we have assigned some agency, its work would generally be associated with moderate rates of dissipation of intermediate to large energy gradients as mediated by a dissipative structure. (I leave aside the negative work of warfare and other explosive applications like strip mining.) Dissipative structures range from drainage systems, through tornadoes and cyclones to biological organisms and human machines. They are interposed between mega through macro to mesoscopic energy gradients (like sunlight) and primary entropy production at the microscopic level. The living cell is something of a special case in that it is itself microscopic. But it is clearly an agent, and is dissipative in generating ATP from energy gradients of much larger scale than itself.

It has been remarked that if there is an energy gradient, then sooner or later a dissipative structure will form in apposition to it, or will discover and degrade it -- and the bigger the gradient, the sooner will this happen (Schneider and Kay, 1994). This is the basic physical understanding of all the lively things we see around us all the time -- forms which mediate entropy production by, e.g., pushing, lifting, rending, impacting, swerving, jumping, streaming and stirring -- that is to say, various convective energy flows. These include rivers, winds, animals, trains, birds, and so on and on. This realization allows us to see that manifest dynamic forms of every kind are products of the Second Law of thermodynamics working as a final cause. Each material form as a functional part of a system reflects a particular style of entropy production -- for example, the leaves of plants are shaped to maximize the evaporation of water from them. The material and formal causes of this multiplicity of systems vary with the kind of system, while efficient cause is that which triggered, released, or forced the appearance of a dissipative structure at some particular time; efficient cause is therefore the motor of history, which is the source of information.

HISTORY AND INFORMATION

All information is a result of historical contingency that gets embodied in material arrangements. A very simple example would be an obstruction in a stream deflecting its flow. This obstruction might be a boulder that fell into the stream during earthquake tremors. It is my view that even the fundamental constants of physics can be understood in this way. They would have been logged into the Universe during its expansion. For example, the force of gravity can be viewed as being scaled by the expansion rate of the Universe, as a kind of negative effect of that expansion, expressing the degree of matter's lagging behind the expansion of space (implied in Nicolis, 1986). (To get a feeling for this, note that, should the expansion decelerate, then the force of gravity would become diminished.)

In any case, we need to find some definition of information, and it appears that there are several, each of which has some use. I find three aspects of information that, taken together, cover most needs, as follows:

From information theory we have:

(1) information is a reduction in variety, or a decrease in uncertainty (Shannon and Weaver, 1949).

From a materialist perspective we have:

(2) information is any constraint upon entropy production.

From a semiotic perspective we have:

(3) information is a difference that makes a difference to some system of

interpretance (Bateson, 1972).

Taking them in order, first:
(1) we can see that the world is easily conceived as a plethora of confusing configurations and events. Its 'informational entropy' or variety of possible configurations, if it could be measured would therefore be very large. But we need to make sense of this world, to organize our view of it. This entails ignoring much of what confronts us, and focusing on the relatively few objects and arrangements that we are geared up to deal with, basically from a pragmatic perspective. When we have reduced the great variety confronting us by ignoring most of it, we can focus upon events, processes, and objects that have a prominent role in our 'Umwelt' (the surrounding world afforded by our biology and culture, and to which we are attuned -- Uexküll, 1926). In this reduced observational field we still need to ascertain which of their possible states our various observables have accessed. When we have accomplished this, we have created information of use to us, perhaps only by having narrowed the observation field to a few of many possibilities. So, in general, gaining information results from a process of reducing informational entropy. A system has an interest also in maintaining a variety of potential responses to environmental perturbations (Ashby, 1958), and so it maintains its own store of informational entropy as part of an overhead of reserve actions (Ulanowicz, 1997).

(2) It has been noted that we need to distinguish between dynamical processes and the informational constraints mediating them (Pattee, e.g.,1977). Functionally, information is that which constrains the results of dynamical processes. This relation is frequently modeled by the distinction between the values of constants in an equation describing some process (the information) and the form of that equation (representing the dynamics). In the World at any moment all potential informational constraints have acquired some configuration or other, garnered during their history, remote and/or recent. Some constraints, like the force of gravity, seem to us to be fixed, others may change from moment to moment, so that we always need to 'catch up' to any current situation. Informational constraints make up the Aristotelian formal causes of events. As such they are the current situation, whatever that may be, at any given locale.

(3) It may not have been noticed, and I did not point it out, that aspects (1) and (2) of information implicitly would have to be tied to some particular observing system. Concerning (1) information theory explicitly refers to the 'receiver' of information. This allows us to distinguish between different kinds of noise in the information channel -- between ambiguity, which may be generated in part by the receiver, and equivocation, which derives from the sender (Dretske, 1981). In regard to (2) if we have several observers confronting some natural locale, it is quite likely that they are not all attuned to the same properties, and their interests will be dependent upon different combinations of informational constraints (Salthe, 2001a). So information, like work in thermodynamics, is not a simple objective property of the world like matter or spacetime. What counts as information depends upon an observing system -- or, in semiotic terms, a system of interpretance -- which is prepared to interpret any information received that might make a difference to its interests.

Finally, it is convenient in the context of information to discuss a hierarchical perspective different from that reviewed at the beginning of this article -- this is the scale hierarchy (Allen and Starr,1982; Lemke, 2000; Salthe, 1985, 1988, 1991, 1993, 2002a, 2006b), as in:

[earth **[** biome **[** population **[** organism **[** cell **[** macromolecule **]]]]]]**

interpreted as **[** higher level **[** lower level **]]**

This is important in the information context because these levels mark different informational realms that are screened off from each other by the inability of processes or events at the different levels to directly interact. This is because the dynamics at these different levels differ in rates of change by at least an order of magnitude. So, the molecular level experiences much faster change (or acceleration) than the cellular level, and so on. Consequently these scalar levels are isolated informational realms embodying formal causes nested within each other. This is an arrangement that may be postulated to maximize the amount of total informational constraints that could be crammed into any one locale, and which I have suggested also maximizes entropy production at any locale (2004c).

Any given level experiences (or interprets) the next lower one as relatively stable ensemble properties (like temperature) or averages (like density or concentration), while it experiences the next level above as normally unchanging boundary conditions (as the force of gravity appears to us) (Lemke, 2000). And so an organism cannot know any of its constituent cells or feel their individual changes, and, on the other hand, it finds its population to be just an aspect of its usually unchanging surrounding environment. Environments are relatively unchanging precisely because their changes are generally slower than changes at an experienced focal level. Here we see that the (non-recursive) constants in an equation describing some dynamical process represent information derived from different scalar levels than the focal level where the dynamics are being observed (Salthe, 1993). Therefore different levels in a scale hierarchy transact indirectly by way of mutual contextualization, which is a non-dynamic, completely informational relation.

Early in its analysis the scale hierarchy was realized to be a structure that favored system stability to perturbations because disruptions at any given level could not as a rule be transmitted directly, as a disruption, to the next level up or down (Simon, 1962). A level higher than where a disruption occurred would simply ‘sum over’ the total lower level property that was involved in the disruption, usually recording a relatively minor change in some average property. Even perturbations originating at higher scalar levels, such as violent storms would be for us, are moderated by intervening levels (Allen and Starr, 1982) -- in this case, for example, by protections from surrounding forests, flood walls, or cultural traditions preserving our social system even when its material infrastructure has been destroyed. In cases where an intervening level does not protect a lower level from a higher level dynamical perturbation -- for example, in a lighting strike from the level of a continental scale weather system impacting an organism, the result is damage to lower level. Orderly dynamics at any level depend upon protection from situations generated by the higher level dynamics afforded by intervening levels. This is perhaps the major function of informational organization in a material system.

SUMMARY

This paper presents an effort to bring the Unity of the Sciences perspective to bear upon the construction of a contemporary Natural Philosophy. My effort is organized around Aristotelian concepts of causality and development.

First I construct a specification hierarchy to organize scientific contributions to our understanding of what there is in Nature. This models higher integrative levels, like the human sociopolitical, as informational refinements of more generally present lower levels, like the physical, with the whole structure acquiring ever more informational constraints as we pass into the higher levels. As a result, each more upper level opens up new degrees of freedom even as it further constricts lower level degrees of freedom. Upper level forms integrate lower level processes under their emergent rules, but they do not transcend the lower ones; rather they supplement them. In this sense the ontology represented is, loosely speaking, 'materialist'. All of our scientific knowledge is potentially representable in this form.

Then I point out that this hierarchy implicitly models a process of development, wherein higher levels emerge from lower levels which foster them, as when we see biology emerging from a chemical background. Emergence is modeled by a synchronic reading of the hierarchy, but is also projected back to earlier times when, presumably, biology for example, first emerged out of chemical forms. Using this diachronic interpretation of the specification hierarchy, we can represent using it a history of the universe following the initiation of the Big Bang.

Any process of change invites some scientific understanding of what is driving and motivating that change. The Big Bang is taken to be the ultimate efficient cause, as it gave rise to a radically disequilibrated universe, which gave rise simultaneously to the force of gravity and the Second Law of thermodynamics. With the Second Law acting as a final cause, energy utilization in work promotes Universal energy equilibration even as it constructs new forms, because of the generally poor energy efficiency of effective work.

Then I point out that there can be discerned two kinds of change -- development and individuation (or evolution). Development can be constructed out of predictable changes observed in any kind of system, and can be given the form of a sequence of developmental stages. Individuation occurs as a system logs in changes resulting from historical contingency. Physical dynamics and chemical rearrangements are subordinated to developmental control in any kind of higher level system. But since systems themselves have origins, this control is mediated by historically contingent information. Historical events are the origins of all information, and so we can say that Universe 'evolves'.

The paper concludes with a description of the major form by which information is deployed in the world -- the hierarchy of scale. This hierarchy models the fact that changes occur over a large span of rates, from the fastest submicroscopic rates to the slowest changes at the largest scales. So different dynamical rates generated by the

expansion of the Universe are the source of mutually isolated informational realms at different scales. Entropy production occurs at the smallest scales, but it is mediated by dynamics constrained by informed structures at intermediate scales. These represent formal causation allocated to different levels that are dynamically screened off from each other by rate differences of at least an order of magnitude.

I would like to acknowledge interesting comments on this text from John McCrone.

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