Timeless Laws in a Changing World: Reconciling Physics and Biology

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ABSTRACT

A major goal of science is to discover laws that underlie all regular phenomena. This goal is best satisfied by eternal principles that leave fundamental properties unchanged and unchangeable. Science has been forced to accept that some processes, especially biological processes, are inherently time oriented. It can either forgo the ideal of universal principles, and account for temporality through specific boundary conditions, or else incorporate the sources of change directly into fundamental principles that are the same for all times and places, and for all temporal scales. In the past, unifying principles adequate for biology have caused trouble for physics, and vice versa. Recent work at the intersection of non-equilibrium statistical mechanics and information theory suggests that physics and biology can finally be reconciled.
Modern theoretical science, like its speculative Greek predecessor, looks for unifying, universal, unchanging laws underlying the flux of experience that can account for all non-accidental patterns or regularities. Whether or not such laws exist, scientific theories have generally been judged not only by their empirical accuracy, but also by how close they come to this Platonic ideal. Even adamant anti-realists seem to agree that theories that fit this ideal are, in some way, better than theories of roughly the same empirical adequacy that do not.

A unified set of universal and complete laws should not leave any widespread patterns to be explained as the effect of accidental boundary conditions. This requires incorporating sources of regular change across space or time, whether macroscopic or microscopic in scale, and whether quantitative or qualitative, into the set of laws. The only possible exceptions are unique but cosmic events such as the origin of the universe. Throughout the history of science, various patterns have resisted this sort of unification. This resistance has been an impetus for major changes in scientific theory.

One of the more difficult areas of resistance has been the reconciliation of physics and biology. There are two dimensions to this problem. The first is the temporality and directedness of biological processes, in contrast to the permanence and indiscriminate nature of physical processes. The second is the importance of forms, or qualitative properties in biology, in contrast to the quantitative nature of physics. These divisions are not precise, by any means. They are more a matter of degree than kind. The boundaries have shifted with changes in our understanding of both physics and biology. Nonetheless, the contrasts remain large enough to epitomise the difficulties in unifying physics and the life sciences.

Broadly, there are two ways to account for regular changes across time. One can either invoke explicitly temporal laws, or else subsume all change under cyclic patterns. The natural way to deal with any recalcitrant phenomenon is to find ways to fit them into one or the other of
these patterns of explanation by extending analyses of phenomena that are already understood to the recalcitrant phenomena. This method implies that we should first try to isolate and explain especially stable phenomena, take these phenomena as the norm, and then generalise our explanations by considering special conditions. Ironically, the method of extending analyses of simple cases to complex ones has often uncovered problems with the explanation of the initial cases.

The traditional place to look for stability (other than in numbers) was in the heavens (Farrington, 1969), which are regular enough and permanent enough to set our clocks by. It is not surprising that the sky was widely believed to be the home of the divinities. The first problem for empirical science, once it arose, was to account for the causal order of phenomenal experience in a way compatible with heavenly order. Aristotelian views of causation, which emphasised teleological explanations, had an implicit temporal order, but also explained change in terms of eternal and cosmic ends. On the Aristotelian view, the null state (the state not requiring special explanation) was the state in which each entity pursues its individual telos, as determined by its essential form. Formal causes provide the motivation, whereas efficient causes provide the means.

The Aristotelian conception of the world\(^1\) permitted perceived change and development to be reconciled with eternal truths, ultimately grounded in the Unmoved Mover. The normal state of affairs is change. But the end state, when the telos of everything has played out, is the equilibrium that comes from the satisfaction of ultimate ends. Things were, on this view, prevented from going directly to their ends through interactions with other things. Especially important were the effects of the circular motions of the heavens, which cut across the patterns

\(^{1}\) I do not refer specifically to Aristotle's physics here, but to the prevailing methodology from somewhat before his time to well into the Christian era. Phenomena and their explanations were generally made sensible through Aristotelian metaphysics. I rely mostly on Kuhn (1957), Farrington (1969) and Losee (1980: 5-26). The varied criteria for accuracy in textual interpretation among contemporary academics would make it foolish for me to claim to be interpreting Aristotle faithfully. All I claim to be representing are dominant themes in the intellectual style that I call Aristotelian. The same considerations apply to my references to Newtonian science.
of worldly life (Kuhn, 1957: 84; Farrington, 1969: 96). Though teleological explanations are close to our own experience, celestial phenomena are not, and the motive of the heavens was mysterious in its eternal cycles.\(^2\)

There is a clear distinction between celestial and mundane Aristotelian physics (Kuhn, 1957: 91). Celestial motion was circular and eternal, while terrestrial motion was rectilinear, temporary and radial (Galileo, 1967: 14, 18). Both of these assumptions are in approximate agreement with common sense observation. These distinct kinds of motion were unified by common explanatory principles which were grounded in the presumed essences of the things whose motion is to be explained. Everything was thought to act out its nature, from the most mundane rock, through humans, to the most exalted things in the heavens. Minor deviations were due to accidental impediments. All the laws of nature were conceived as relations of essential properties that themselves never change. The apparent order in the heavens was seen to reveal the most basic properties of nature. Heavenly motion affected the mundane world by deviating terrestrial bodies from their linear paths. Thus heavenly motions lay behind the contingencies of the terrestrial world. One of the deepest of truths was expressed by the dictum, "As above, so below". Astrology was a science.

Biological change was most easily understood, since each thing acts in accordance with its essential form, in order to realise its nature. Lions are lionly, dogs are cynical, and humans are rational. Acorns strive to express their internal essence by growing into mighty oaks. Deviations from the essential forms are defective accidents\(^3\), and in extreme cases are abominable monsters. Reproduction passes on the essential form of the kind, and development expresses the essential qualities of each individual, barring accidental interference. On this view, nature determines

\[^2\] Farrington (1969) pointed out that the Pythagorean-Platonic perspective adopted by Aristotle defeated atomism specifically through the former's placement of what Farrington calls the supernatural in astronomy. Farrington claimed that the atomistic view was superior in its reliance on naturalistic laws alone, and that science was hampered by Pythagorean superstitions. I think gives more credit to the atomists than they are due. The Aristotelian view discriminates motives through the essential properties of natural things, but the atomists had to resort to \textit{ad hoc} differences in form to explain different motions, particularly between the planets.

\[^3\] Unlike in the joke, a pig missing one leg would not be an especially good pig, but a defective one.
The main problem was the efficient cause of heavenly motion. If we assume that each heavenly sphere is (nearly) concentric on the inner spheres, each sphere could have its own motive. Unfortunately, this plausible assumption violated close observation. The planets cannot be on concentric spheres. To account for observed motions, supplementary spheres were required, providing epicycles, deferents and eccentrics. These spheres, however, would collide with each other, causing a disturbingly unheavenly interference. The possibility of elliptical orbits never occurred to the Ancients. Circular motion was not thought to require special explanation, unlike deviations from circularity.

Despite its conceptual elegance, Aristotelian physics was not well suited to the explanation of celestial dynamics. The complexity of celestial motion, despite its apparent cyclic simplicity, defied dynamical explanation. The efficient and material aspects of celestial causation became less of a concern as celestial motion became more completely described (Kuhn, 1957: 105). The resulting decline of speculative science led to the view that a theory was adequate if it "saved the phenomena" (Losee, 1980: 19-20). This was perhaps fine for the late Greeks, but sat uncomfortably with the absolutism of Medieval Christianity. Theoretical science took a back seat to theology.

The division into the celestial and mundane realms undermined the unity of science, and upset the symmetry between heaven and earth. It became a reasonable scientific task to try to reconcile the two, most obviously by bringing the heavenly order to earth. Astrological research (Kuhn, 1957: 92-94), squaring the circle (making circular and rectilinear motion commensurable), and transmutation of elements in the hope of isolating the "quintessence" manifested in the heavens became reasonable scientific research programs. Despite technological successes and some theoretical advances, science did not have much to offer. Most of the effort of the best minds was put into theological approaches to unity. Scholastic science retained the Aristotelian notion of causal qualities that provide the inner motivation for a thing's regular properties.

With the Renaissance, secular concerns became more significant, and speculation revived together with increased exploration and technological change. Galileo (among others) discovered destiny, shaping all predictable changes. The only other things needed are the material substrate and the actual physical connections. Together, the essential and material connections provide the formal, final, efficient and material causes required for change.

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regularities in terrestrial movements that reflected the regularities of the heavens. He thought that all motion must be inherently circular, and that it was only the "material hindrances" of our senses that prevented us from directly perceiving the circular nature of all change (Galileo, 1967, especially the beginning of "The First Day"). The plausibility that the universe was a single domain gradually increased with the recognition that the heavens were not as perfect as they first appeared. Materialist and mechanical explanations were proposed as the best way to unify heaven and earth. Hobbes even thought he had squared the circle by rational means. Finally, Newton, overcoming his early acceptance of circular motion as natural, provided the canonical form for the new laws that seemed likely to unify all phenomena (Newton, 1966: 13). The mechanical view of the world that grew out of his laws extended the mundane order to the heavens, but, ironically, left little room for temporal development on earth.

Newton's mechanics assumed that the normal or null state of physical things is neither to strive for an end nor to persist in eternal cycles, but to continue in a straight line forever (Newton, 1966: 2, 13). This notion gives eternity entirely new connotations. On the mechanical paradigm, all non-rectilinear motion is due to applied forces that, except for the few conservative forces producing cyclic motion, are by their nature temporary. The mechanical philosophy could explain uniformity and regularity of motion most easily, because in Newtonian theory the null state is the one in which there is no deviation. Non-uniformity and irregularity require special explanation. Temporal order can be reversed merely by reversing the applied forces. There is no fundamentally preferred temporal direction in the Newtonian world.5

Perhaps the most significant feature of the Newtonian revolution is its revision of the locus of action of forces. On the Aristotelian view, formal essences imply final causes that are the origin of motives or forces. Deviations are the result of accidental interactions with other things, resulting from the particular contingencies of the world. On the Newtonian view, the null

5 This is not exactly correct, since friction was known. Friction induces non-conservative forces that determine a temporal direction. I am indebted to Keith Hutchison for reminding me of this fact, which should be entirely obvious, but is often not apparent. Nonetheless, the mechanical paradigm assumed that all forces at the microscopic level are conservative. This assumption became so firmly entrenched in mechanical thinking that alternatives have been explored only recently.
state is a no-force state. All forces produce deviations through external action. Although there are innate properties, there are no innate forces. Forces arise from the expression of the laws of nature, the exact expression depending on the relative properties of material things. These relations, or boundary conditions, are accidental, and are not themselves governed by law. Like the accidental aspects of Aristotelian interactions, they can only be determined by particular observations. Laws, which are ideally universal and general, reduce the number of independent properties by regularising the description of individual interactions. Efficient (mechanical) causation is fundamental, and change in form is merely a consequence. Apparent formal causes are merely an epiphenomenon of the underlying laws, accidental arrangements, and efficient causation.

Under the mechanical paradigm, vitalist explanations of organic function were rejected because they presumed that causes were intrinsic qualities. This reversed the reasons for rejecting mechanical explanations under the Aristotelian paradigm. The most successful explanations in the life sciences were mechanical proposals in physiology, though this sort of explanation was applied widely to all bodily function, such as Descartes' theory that the nerves transmitted hydraulic pressures. Form entered into mechanical explanations solely through the way it guided mechanical forces (the nerves as passive tubes, or the kidney as a sort of sieve). There was less success in explaining more complex organic functions. The circulation of the blood (Harvey) could be understood mechanically, but reproduction and ontogeny was intractable, despite bizarre speculations.

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6 Hutchison (1991) describes the replacement of the qualitative essentialist view of causes by the mechanical view, which was more completely adopted by Descartes than Newton. Newton was ambiguous about the possibility of some qualitative causes.

7 At the high point of the mechanical philosophy, animistic explanations of vital processes were dismissed as trivial (King, 1972: 12-15, Brown, 1974: 186). Descartes (1972: 113-115) thought that vitalistic explanations were entirely superfluous. On the other hand, Galen once thought much the same thing about mechanistic explanations (Galen, 1916: 86).

8 Many of these explanations involved a motive power in the sperm, which transferred its mechanical activity to the passive matter of the ovum. This implied, naturally, that all of the mechanical capacity of a full-fledged organism should be contained in the sperm. This was often visualised as a tiny "homunculus" contained in the sperm. Although this thinking was at least partly on the right track, its sexist presuppositions should be evident.
Proponents of teleology and vitalism argued that mechanical explanations of life were inadequate. Though they often used metaphors from the physical sciences, such as heating and cooling, these were usually conceived as sentient responses, and were combined with organic notions like fermentation. A rift, or at least a gulf, formed between the life and physical sciences that hasn't been adequately bridged even now. One fundamental problem was the apparent incompatibility of Newtonian time-reversibility with the temporal directedness of most life processes. One aspect of the directedness of life is its apparent purposefulness, or at least functionality, which invokes qualitative relations between means and ends. These don't sit well with the efficient causality of the mechanistic philosophy. The life sciences still tend to invoke Aristotelian final causes, if only as a metaphor.\(^9\) Much of biology since Darwin has tried to purge itself of this reliance on teleology.

Friction was recognised as a force that dissipates energy, and the temporal directedness of damped processes was not considered unusual. Any potential problems were overcome with the development of the mechanical theory of heat (Brush, 1976). With the development of thermodynamics in the 19th Century, it was recognised that mechanical processes could dissipate energy, and that dissipative processes have a unique temporal direction. But no one assumed that the creative forces of life could arise from dissipation. Life appeared to be ordered and purposeful, while dissipative forces were disintegrative of order. Thermodynamics was sometimes thought of as "the dismal science." Friction makes things run down, whereas living things appeared to have an inner motive.\(^10\)

Within the mechanical view, the apparent discrepancy between the physics and life was attacked from two directions. First, Darwinian views of evolution still current today reduced the importance of apparent purposefulness in life by explaining the functional traits of living things as the result of chance mutations selected for their propensity for survival (Darwin, 1859;...
Dawkins, 1987). Selection was conceived as a mechanical process by which the environment imposed its structure on the random variation of biological material produced by the genes (Sober, 1984). The resulting regularities were a consequence of an equilibrium between environmental forces and genetically determined traits having randomly varying survival propensities. On this view, biological function is time-directed by past selection processes that enhance the average likelihood of survival. The direction is away from the past, rather than towards the future. The appearance of purposefulness is an artefact of past selection that has eliminated less functional varieties (Dawkins, 1987). Order in life, on the other hand, is a consequence of the imposition of environmental forces, and is not produced from within living systems themselves. In line with the difference between the Aristotelian and the Newtonian views of causation, Darwinism reverses the locus of the causes of regularities from inner essences to external boundary conditions. Since living things themselves produce only chance contributions to the process, evolution is governed by accident. This supports an often voiced view that there are no strictly biological laws. Any regularities in biology, on this view, are a reflection of either historical regularities or else physical laws.

The second direction of attack on the problem involved giving mechanical processes a temporal direction. Given the Darwinian account of life as the product of chance mutation and environmental forces, the temporal direction of living things, even in the short run of the lives of individual organisms, must be the effect of an underlying physical anisotropy. The major source of temporal anisotropy in physics, at least in macroscopic physics, is dissipation. On the mechanical paradigm, dissipation must be accidental, usually presumed to be an epiphenomenon of the conservative underlying order. Although the mechanical paradigm had the resources to account for temporal directedness, it had no means to incorporate this directedness as a law-governed regularity. This required an improved understanding of chance.

The role of chance gradually took on a greater prominence as a challenge to the mechanical world-view. Concern with chance events, motivated by the pragmatic concerns of intelligent gamblers, led in the mid-1600's to the development of statistics (Hacking, 1975: 11). The general view of chance, however, remained that it was merely a reflection of human
The equilibrium assumptions embedded in the methodology were known to be false, so the problem was more one of bringing theory and methodology into line with the phenomena than a fundamental problem of knowing what was wrong with the theory. The theory was caught in the Newtonian paradigm, but scientists were becoming aware that the world was not ignorance (Hume, 1748). Probability was originally associated with opinion, and even now is taken by many to be merely the weight of evidence (Hacking, 1975: 22, 31). By the 19th century, however, statistical analyses of physical processes passed beyond the merely descriptive and predictive to the explanatory. Maxwell's statistical explanation of the dynamics of the rings of Saturn led the way. It showed that explanations of macroscopic phenomena could involve underlying chance events.

The development of evolutionary theory and thermodynamics in the last century brought temporally directed phenomena firmly into science. These theories, however, were developed largely under the influence of Newtonian views in which the state of no action is natural. Statistical phenomena show no change (except for minor fluctuations) when they are in equilibrium. This is the closest analogy to the Newtonian state of no action, and became the basis for the extension of the Newtonian world view to statistical phenomena.

Although the mechanical paradigm had the resources to account for temporal directedness, it had no means to incorporate this directedness as a law-governed regularity. Likewise, statistical mechanisms that presume that the null state is equilibrium have difficulties with temporal anisotropies. Change had to be conceived as the result of forces applied to the equilibrium null state. Statistical phenomena were investigated under the assumption that the systems involved were close to equilibrium, or else were under the influence of intentional direction, as in mechanical devices and artificial selection. The introduction of statistical mechanics, which for Boltzmann were inspired by Darwin's contributions, caused grave problems for reconciling the apparent time-reversibility of micro-physics with the directedness of thermodynamics. Since calculations in thermodynamics were made through reference to changes under equilibrium conditions, there was a divergence between methods and observed conditions. Because equilibrium changes are reversible, the methods used suggest that in principle all thermodynamic processes should be reversible, but it was known that they are not\footnote{The equilibrium assumptions embedded in the methodology were known to be false, so the problem was more one of bringing theory and methodology into line with the phenomena than a fundamental problem of knowing what was wrong with the theory. The theory was caught in the Newtonian paradigm, but scientists were becoming aware that the world was not.}. These
problems were not resolved by the reduction of thermodynamics to statistical mechanics. Statistical mechanics generated paradoxes such as Loschmidt's paradox of time reversibility and Poincaré's recurrence paradox (see Collier, 1990 for discussion).

In biology, the problems surface in the difficulty Darwin had in explaining speciation, and later difficulties in explaining Dollo's law that evolutionary forms do not repeat themselves. Contemporary population biology (e.g., Ginzburg, 1983) generally assumes equilibrium conditions with deviations and return to a new equilibrium. Evolution is widely regarded as a local phenomenon with no inherent direction.\textsuperscript{12} Mathematical analyses of speciation events or unidirectional evolutionary patterns are rare at best. These difficulties, and others, have led many writers to argue that evolutionary biology was not a normal science, but more of a historical study. The same might have happened to thermodynamics and statistical mechanics, except that they were so decidedly \textit{physical}. The closest thing to a historical component in these sciences are proposals that the thermodynamic arrow of time is a consequence of the origin of the universe in a highly condensed state.

The historical aspect of thermodynamics has the advantage that it is cosmic in proportion. The non-equilibrium order in the universe can be attributed to incomplete dispersal from the Big Bang. There is something analogous for life, however: its origin in simple chemical forms. Unless evolution is understood macroscopically from its sources in the origin of living things, there is little chance to rebut the charge that there are no specifically biological laws that are not just consequences of physical and chemical accidents. If there are laws governing the origin and evolution of life that are common to all living forms, this charge can be rebutted. This rebuttal will be stronger if it can be shown that the mechanisms involved are not dissimilar to those that produce temporal directedness and organisation in physics.

\textsuperscript{12} A recent biology text (Luria, Gould and Singer, 1981: 647) states "Darwinism is not a theory of intrinsic progress," going on to note that adaptations are local only. An account of organisation in terms of selection alone could account only for local changes that increase fitness. Other locales and other times could easily lead to adaptive decreases in the same organisation, particularly if environmental conditions go through long cycles. The problem is discussed in more detail in (Collier, 1987; 1989).
In physics, temporal directedness and organisation have been found to originate in non-equilibrium processes. Non-equilibrium conditions themselves imply that physical processes will be directed. Work in non-equilibrium thermodynamics, notably by Prigogine and his school, showed how non-equilibrium conditions can lead to self-organisation at macroscopic (higher) levels under certain conditions. The process involves the amplification of microscopic fluctuations to macroscopic scale. Often this involves chance branching of systems towards one or another macroscopic attractors. It is possible for different parts of a system to branch in different ways. Most close technical analyses of such systems are of near to equilibrium systems. These are defined such that the size of the statistical fluctuations of the properties of the state are less than or equal to the gradient of these properties within the system. These systems usually form stable dissipative structures, not evolving entities. Nonetheless, there is some reason to believe that self-organisation is at least as likely under far from equilibrium conditions, although it will occur in response to applied forces, rather than more generally in response to the local thermodynamic gradient. Prigogine's work suggests that the system will rearrange itself to reduce the local entropy production in the direction of the applied forces. Rod Swenson (1989) has suggested that this always increases total dissipation through the system. These two conditions, local minimisation and global maximisation of entropy production, govern the re-organisation of systems that are subject to external forces. The complex interaction of far from equilibrium systems allows the possibility for the formation of complex and highly organised systems, with mutually interdependent relations. In general, systems do not respond to external forces in the simple linear way presumed within the Newtonian paradigm, but respond by manifesting previously implicit order.

The origin and maintenance of the non-equilibrium conditions necessary for both temporal anisotropy and self-organisation comes from expansion of the phase space of the system. Phase space expansion models allow order and disorder to increase together, allowing

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13 See Prigogine (1961) for the basic theory of dissipative structures, and Nicolis and Prigogine (1977) and Prigogine and Stengers (1984) for applications to a broad range of systems.

14 A good reference on systems with expanding phase space is Layzer (1975). See also S. Frautschi (1982; 1987) and P.T. Landsberg (1984). The latter references consider general
new complex forms to evolve within an entropically driven anisotropy. The expanding phase space of these systems results from the formation of new possible states as the result of differentiation of the system. Since there are more possibilities in the direction of the expanded phase space, a system undergoing chance fluctuations will tend to evolve into the expanded phase space. (There are more states to evolve to in that direction.) This tendency of a system to move towards states with more possibilities is the basis of the Second law of Thermodynamics.

There are two basic strategies for applying these ideas to biology. One is reductionist, basing all biological evolution on physico-chemical processes. One exponent of this approach is Jeffrey Wicken (1987), although he denies being reductionist. Wicken distinguishes thermodynamic entropies from others. He argues that the strict thermodynamic sense is the only justified sense. His arguments have tended to rely on claims about linguistic usage, which may have little to do with natural facts. His approach is defective because he does not come to terms with the role of forms as well as physical processes in explanations of biological evolution (Collier, forthcoming). For example, Wicken must assume that energetic efficiency drives selection. But this is far from clear, since in many biological systems there is energy available in far greater abundance than is used. This suggest that historical constraints are more significant than environmental constraints. Nor is it obvious how speciation can be understood in terms of thermal entropies, since speciation events are generally described in terms of restrictions on the exchange of genetic information. It is not clear how temperature, heat, or energy are relevant.

There are number of current approaches that explain the directedness of biology in terms that are compatible with mechanical (efficient) causation. Examples are (Mayr, 1982: 609), (Dawkins, 1987, especially chapters 7 and 8), (Kauffmann, 1991; in press), Schanck and Wimsatt (1988). These approaches differ from each other, and do not explicitly invoke the non-equilibrium paradigm. Nonetheless, I consider these approaches to be incomplete renderings of the non-equilibrium paradigm, since they rely on the assumptions of the paradigm tacitly where not explicitly. Many proponents of these approaches would disagree, but to demonstrate my claim would take far more space than this whole article. Instead, I will argue that the intuitive plausibility of each approach suggests an underlying unity. The fact that the techniques of each of these authors requires non-equilibrium conditions suggests strongly that the non-equilibrium paradigm is the proper one for unification.
The second approach applies the principles of non-equilibrium processes directly to changes in form, via information theory. Schrödinger (1945) noted that living systems maintain and increase their form by sequestering information that is available in the environment. He saw the development of life as fundamentally negentropic. Lila Gatlin's (1972) pioneering work showed that there is reason to believe that living systems spontaneously increase their information content. On the equilibrium view coming from the application of the Newtonian paradigm to biological processes, this is paradoxical at best. D.R. Brooks and E.O. Wiley (1988) resolved this paradox by applying the notions of self-organisation through dissipation and the maintenance of non-equilibrium conditions through expanding phase space directly to information within living systems. This approach required some revision of standard information theory (see Collier, 1986), but basically assumes that information has macrostates and microstates analogous to those of physical systems.\textsuperscript{16} If the information and energetic systems are sufficiently decoupled, the two can be treated separately.

This approach allows the explanation of Dollo's law and the branching structure of both development and evolution within a single elegant theory. They are both a consequence of thermodynamic branching within an information system that is far from equilibrium. Self-organisation produces new levels of entities that create new possibilities of interaction, resulting in an increased phase space, driving biological systems continuously into non-equilibrium conditions (Brooks et al., 1989). Internal processes play a significant role in both evolution and development.

On the original version of the Brooks/Wiley approach, selective processes were not incorporated directly into the analysis. This was later corrected by (Brooks et al., 1989) when I noticed that the mutual information of an organism's genome and its environment could also be treated entropically. This allows coordination of the organism and the environment to increase

\textsuperscript{16} This point should be emphasised. Thermodynamical analysis presumes a distinction within the system between microstates and macrostates. The cohesion of a system at higher levels makes it resistant to fluctuations in its microstate, and makes the macrostate distinct. One consequence is that it is impossible to control the microstate of the system with the resources of the macrostate. So at least some changes in microstates are effectively random with respect to their corresponding macrostates. These issues are discussed in more depth in (Collier, 1986; 1988; 1990; 1991).
spontaneously, according to the principles of non-equilibrium theory. The exchange of information in ecologies can be understood with the same principles. This completes the integration of biology into the non-equilibrium paradigm.

On the non-equilibrium approach, the null state is non-equilibrium, leading to change towards greater complexity, differentiation and organisation. Contrary to the Newtonian paradigm, it is constancy that needs special explanation. In this respect the new model is more similar to Aristotelian science. Another similarity with the Aristotelian view is that form plays a central causal role, although teleological implications are left behind. Self-organisation internalises some causes within systems, so that historically determined conditions rather than boundary conditions can dominate. On the other hand, these historical conditions are just as accidental as boundary conditions in the Newtonian paradigm. Perhaps more so, since branching towards different self-organised states depends on the amplification of chance fluctuations. Self-organisation allows the formation of partially independent levels that forestall reductionism. This permits changes in form to be studied with the same general principles as those that govern mechanical systems. These general principles are the timeless laws that imply a changing and evolving world. The formation of new kinds and levels of organisation implied by these principles ensures that there will be a multitude of highly organised original states that are both historical and accidental, but also inevitable.

References


Collier, J.D. (forthcoming) Out of equilibrium: new approaches to biological and Social Change *Biology and Philosophy*.


Hume, David (1748) *Philosophical Essays Concerning Human Understanding*, London. (Subsequently titled *An Inquiry Concerning Human Understanding*.)


