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Instructionism is Impossible Due to the Second Law of Thermodynamics

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Spiders' nests, birds' wings, airplanes, and scientific theories are all instances of adaptations. Instructionist theories (analogous to Lamarckism) implies that adaptive novelties are imposed directly on an entity by the environment (from without) while selectionist theories (analogous to Darwinism) explains adaptive novelties to be the product of mechanisms including trial and error (from within). This article argues that adaptive novelties are the result of selectionist mechanisms while instructionist production of adaptive novelties is impossible due to the second law of thermodynamics. Even long-term preservation of adaptive information is dependent on selectionist mechanisms. These findings have important implications for both human and societal development because of the prevalence of instructionist theories.

> The law that entropy always increases — the second law of thermodynamics — holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations — then so much the worse for Maxwell's equations. If it is found to be contradicted by observation — well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation. (Eddington, 1929, p. 74)

Four billion years ago the Earth was a barren, lifeless planet. Now it is covered by a huge variety of life adapted to each local environment. Humans and their artefacts abound, and knowledge of the universe has exploded. To be novel a product has to be unexpected (unpredictable). To be adaptive a product must be meaningful or useful in its context. Production of adaptive novelties is apparent in several different domains such as evolution, art, science, technology and culture in general. The aim of this article is to analyse

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evolution in the light of thermodynamics and then to extend this analysis to adaptive novelties. It will be argued that adaptive novelties are the result of selectionist mechanisms while instructive mechanisms cannot produce adaptive novelties due to the second law of thermodynamics.

Instructionism (analogous to Lamarckism) represents the view that the environment (teacher, antigen, trees) can impose adaptive novelties directly on an entity (student, antibody, giraffe's neck). According to selectionism (analogous to Darwinism), adaptive novelties arise through indirect mechanisms. Firstly, a populational process generates random variations of possible order, and secondly, interaction with the environment chooses the "best" variations (Cziko, 1995).

Evolution of life is the prime example of selectionism. However, selectionist mechanisms are also acknowledged in other domains. For example, when organisms become infected by foreign invaders (bacteria, virus), the immune system generates a large number of specific antibodies to the invaders. The production of novel, adaptive antibodies by the immune system is the result of selectionist mechanisms (Jerne, 1967).

Adaptive novelties made by human beings are thought, by some neurobiologists, to be generated by discrete, selectionist neurophysiological processes (Calvin, 1996; Changeux and Dehaene, 1989; Edelman and Tononi, 2000). For example, Calvin (1996) proposed that hexagonal spaciotemporal firing patterns of pyramidal neurons in the human cortex represent possible self-copying units embodying information about both the internal and the external environment. This is a selectionist process where swarms of firing patterns compete to produce the best information.

However, in the social sciences selectionist theories are infrequent. Many anthropologists still believe culture evolves by instructionist mechanisms. Individual human beings are only the formless material directly transformed by culture according to the so-called standard social science model (Tooby and Cosmides, 1992). Likewise, neoclassical economics regards market participants as passive price takers. The economic problem underlying this viewpoint becomes the allocation of scarce means among alternative or competing ends (Buchanan, 1979). All information is known to everyone (the perfect knowledge assumption); novelties are, therefore, outside the neoclassical domain.

Adaptedness

The best way to understand adaptive novelties is to start with the evolution of life. Adaptedness is an informational match between organism and environment. An adapted animal embodies information about its environment in the way a key embodies information about the lock (Dawkins, 1982). Similarly, knowledge is the relationship between a knower and the known. All adaptations are instances of knowledge (Plotkin, 1994).

There are two explanations of evolutionary novelties. Lamarck thought that the environment directly induces a novel, adaptive trait in an organism and once acquired that trait is inherited by the offspring. According to Darwinism, fitter variants of self-copying structures (genes) are selected and by parallel competition the better adaptations gradually come to dominate. Lamarckism represents the idea of instruction from without (from the environment) while Darwinism only allows instruction from within (from the genes). Dawkins (1982) describes the Lamarckian key-maker as one who takes a wax impression of the lock and then makes a good key directly. The Darwinian key-maker on the other hand begins with a large, random pool of keys and tries them all in the lock before discarding those that do not fit. The central dogma of embryology forbids the inheritance of acquired characteristics, but many scientists argue that (including evolutionary biologists like S.J. Gould, P.B. Medawar and perhaps even R. Dawkins) Lamarckian processes are possible outside genetic inheritance. According to Dawkins (1982), complex and adaptive fits like the learning of a particular language is the result of an instructive (Lamarckian) process. I believe this view to be wrong.

Darwinism, Lamarckism, and Thermodynamics

Use of thermodynamic theory can help demonstrate that Lamarckism is highly unlikely. It was Ludwig Boltzman who introduced the macrostate–microstate distinction in the statistical interpretation of thermodynamics. The macrostate of a system (for example a gas) refers to its macroscopic values (like temperature and pressure) while any microscopic arrangement of the system (for example the velocities and positions of the gas molecules) is called a microstate. Thus, a macrostate is a class of microstates that has a common property. The game of poker provides an instructive illustration (Layzer, 1990). A specific poker hand corresponds to a microstate while the categories of flush, straight, three of a kind and so on, correspond to macrostates. Many different poker hands (microstates) represent flush (a macrostate).

A system can be assigned an entropy if any given macrostate in which it resides can be expressed in a variety of alternative microstates. If there are W equiprobable microstates in which a macrostate can reside, then the entropy S of the macrostate is given by $S = k \cdot \ln W$, where k is Boltzman's constant. An ordered macrostate (a cup or the category of flush in poker) corresponds to relatively few microstates while disorder (a broken cup or a random poker hand) is compatible with numerous microstates. There are many more ways for a cup to be broken than whole. Likewise, there are many more disordered poker hands than poker hands corresponding to specific poker categories. Thus, entropy of order is low while entropy of disorder is high.

The concept of entropy is important because of its relationship to the second law of thermodynamics which states that the entropy of any closed system either remains constant or increases. In accordance with the second law, a decrease in entropy is possible locally, but only at the expense of even higher entropy increase elsewhere. Although entropy as a concept first appeared in classical thermodynamics, entropy increase is a ubiquitous phenomenon. Entropy is a quantity of possibilities, like the quantity of possible microstates of a gas in a vessel, the number of ways the letters in a text can be arranged or the different poker hands representing two of a kind (Chalidze, 2000). As will be shown later, the second law is important when it comes to scientific understanding of how adaptive novelties arise.

Genes with slightly differing sequences of nucleotides often produce similar adaptations or phenotypes. There is, therefore, a macro–micro distinction analogous to statistical thermodynamics. I suggest that adaptations can be defined as macrostates whereas the microstates constitute all responsible genotypes. *W* then represents the number of all more or less equiprobable genotypes that code for a given adaptation. Layzer (1988) has given a similar definition assigning proteins with similar functions to a macrostate. Hemoglobin performs the function of transporting oxygen well enough for organisms to survive and reproduce. Many different variants of hemoglobin can do this, and these variants represent microstates corresponding to the macrostate of being able to transport oxygen.

Viewing genotypes as microstates is also compatible with the theory proposed by Brooks and Wiley (1988). Like Brooks and Wiley, I suggest an approach that is based on populations of genotypes and compatible with the anti-essentialist nature of modern biology. Their theory differs, however, regarding the definition of a macrostate which they define as the distribution of individuals over the microstates (genotypes) available to the population of N organisms. In contrast, the definition of a macrostate presented here comprises all possible genotypes (microstates historically realized or not) coding for a given adaptation and is therefore linked to a higher entropy than the observed entropy of the macrostate of Brooks and Wiley. Brooks and Wiley have been criticised for downplaying the role of natural selection (Depew and Weber, 1996). However, adaptations play a key role in biology and focusing on adaptations as macrostates takes account of this.

At the level of DNA sequences, the living state is compatible with relatively few microstates (Elitzur, 1994). The sequences compatible with life are a very tiny minority of all possible DNA sequences (Ridley, 2000). From this it follows that the entropy of adaptations is low. Evolution therefore seems to contradict the second law of thermodynamics. This argument is often invoked by creationists against Darwinism, and its inadequacy will become clear in what follows.

Mutations (microstates) may be viewed as steps toward maximum entropy (disorder), due to the second law that demands increasing disorder. Most arrangements of nucleotides are meaningless and correspond to noise. The Darwinian process searches through a huge space of different nucleotide combinations and occasionally by accident hits upon a few nucleotide combinations representing a possible adaptive novelty. That process includes a huge sink comprising numerous maladaptive mutations. Death of novel maladaptive mutations without reproduction (dissipation or decomposition of harmful mutations) and selective amplification drives the Darwinian process toward populations of microstates representing novel adaptations (macrostates) comprising low entropy while increasing total entropy because different maladaptive mutations by far outnumber adaptive ones. In this way adaptive novelties arise while discarding a vast amount of noise. Usually we do not see this high-entropy noise, because most of it dissipated long ago (eventually as radiation into space). Instead we see the remaining abundant, low-entropy life. As described by Campbell (1967), the winnowing of less fit organisms at each generation may represent dissipation of entropy that drives survivors to a lower entropic form. Thus, the Darwinian generation of low-entropy adaptations pays it debts to the second law by eliminating vast amounts of harmful mutations. This demonstrates that, contrary to the creationist argument, Darwinian evolution is compatible with the second law.

A clarification is needed by introducing thermal and configuration entropies. Thermal entropy is associated with the distribution of energy in the system while configuration entropy is concerned only with the arrangement of mass in the system. The thermal entropy of a DNA sequence coding for an adaptation and the thermal entropy of a DNA sequence of equal length representing noise are more or less similar. However, their configuration entropies are very different, because the first belongs to the macrostate defined by the adaptation while the second belongs to the macrostate of noise. The configuration entropy of the first DNA sequence is very low whilst that of the second is high. A thermodynamic understanding of ontogenetic (individual) development is concerned mainly with production of low thermal entropy as eloquently described in Schrödinger's (1992) famous book *What is Life?*, whereas the generation of unforeseeable, adaptive, low configuration entropy is what phylogenetic evolution is all about. An example can perhaps illuminate the difference between thermal and configuration entropy. The thermal entropy of a whole cup and a broken cup is not very different. Superficially, the amount of extractable work from the whole and broken cup, seems more or less the same. Their configuration entropies are nevertheless very different. The whole cup makes it possible to do work like emptying a bucket of water, a task for which the broken cup is useless. It is the shape of the cup that makes this possible and the configuration entropy of the macrostate of cuplike entities is low compared to the configuration entropy of the macrostate of broken cups.

The above reasoning shows that Darwinism is both compatible with and dependent on the second law and indicates strongly the impossibility of Lamarckism. This is because Lamarckism implies direct induction of adaptive novelties from without while avoiding the maladaptive sink. A better low-entropy adaptation is chosen directly, implying a decrease of total entropy with no overall entropy increase because there is no dissipation of harmful mutations. The first step of Lamarckism (direct induction of adaptive traits from without) seems therefore incompatible with the second law. Elitzur's (1994) thermodynamic proof of the central dogma of embryology gives further evidence that even the inheritance of acquired traits (the second step of Lamarckism) is incompatible with the second law:

> Consider a stereophonic tape-recorder playing a recorded symphony where the tape constitutes the "genotype" while the resulting configuration of sound waves in the air is the "phenotype." If we wish to make a good copy of the symphony, we shall of course copy the tape itself rather than recording the symphony from the air back to the tape. The reason is clear: dissipation considerably decreases the quality of the sound waves arriving at the microphones. In trying to conceive of an ideal recording from the air back to the microphone, we soon realize that this requires a complete reversal of the tape-playing process, i.e. making the sound waves converge back into the microphone, placed exactly at the points where the amplifiers were. Such a reversed phenotype–genotype recording allows "Lamarckian" evolution; one can add, for example, another instrument to the played symphony and then record the improved symphony back into the tape. However, in order for such a process to be efficient, exact reversal of dissipative processes is needed, which is far beyond the energy resources of any realistic project . . . . This example makes, *a fortiori*, any mechanism involving inheritance of acquired qualities impossible. (p. 447)

The meaning is clear: the second law seems to forbid the first step of Lamarckism (directly inducing adaptations), and even if the first step were possible, the same law forbids the second step (inheritance of acquired traits). Thus, the second law doubly forbids Lamarckism. This may not seem a very interesting discovery because Lamarckism was long ago superseded by Darwinism. I believe, however, this is important because processes analogous to Lamarckism are often invoked in areas outside biological evolution and understanding why Lamarckism is incompatible with the second law undermines the Lamarckian explanations elsewhere.

The Impossibility of Instructionism

What about adaptive novelties in other domains? Are novelties of artists, scientists, technologists and humans in general the result of processes analogous to Lamarckism or Darwinism? Outside biological evolution, it is customary to speak of instructionism and selectionism.

Can science or culture ever evolve by instructionist mechanisms? In order to see that instructionism is highly unlikely, it must first be recognized that the configuration entropy of any adaptation (knowledge) in any domain is very small compared to the configuration entropy of maladaptations (noise). Errors or noise vastly outnumber knowledge. The number of ways the meaning of the theory of relativity can be conveyed is small compared to the number of ways a similar amount of letters can be arranged. An illustration of this claim is the difference between work and content according to structuralist realism (Stent, 2001). By work, structuralist realism means the presentational nature of a piece of art or science, while content refers to its propositional nature (meaning). Every propositional content can be presented in different structures (works) in both art and science. If Einstein had not lived, the propositional (semantic) content of the theory of relativity would most likely have been discovered later by someone else and published in a different presentational form (work). I suggest here that work corresponds to microstate and content to the meaningful macrostate of a piece of art or science. There is a parallel here to the genotype–phenotype division in evolution. Human knowledge (corresponding to phenotype) is separated from written or spoken language (corresponding to genotype) analogous to the way phenotype is separated from genotype in evolution. This also applies to music where a symphony (corresponding to phenotype) is separated from its score (corresponding to genotype).

According to Landauer (1990) information is not an abstraction, but inevitably tied to a physical representation. All adaptations (knowledge) are represented by physical systems (brains, genes, books and so on) and are therefore subject to the second law. There is no disembodied knowledge. Any physical system carrying knowledge can be changed to some extent without destroying the meaning (content). In general, for all knowledge there is a macro–micro distinction in accordance with structural realism. Thus, specific knowledge is a macrostate conveyable by many different concrete microstates. This fact is of upmost importance and central to the argumentation below and parallels the thermodynamic argumentation in the previous section.

In accordance with the second law, every change in a microstate is, in all probability, a step toward maximum entropy. In selectionist processes (including copying of microstates) many maladaptive microstates (degenerate "knowledge" or noise) arise for any microstate representing a novel adaptation because of the huge difference of the respective configuration entropies. By means of selective amplification, better adaptations eventually dominate. Respect for the second law is maintained because of dissipation of maladaptive microstates (noise). A total increase in entropy is ensured despite the low entropy of the new adaptations (knowledge). Selectionist processes in general are thus compatible with the second law because of the total rise of entropy.

Instructionism on the other hand means a shortcut toward better knowledge. Instructionist processes jump directly to adaptive novelties without trial and error. This means that instructionism, by avoiding the maladaptive sink, leads to a decrease in total entropy. This is very improbable. Even if this were possible, Elitzur (1994) has shown that any mechanisms involving exact "phenotype" instruction of qualities is impossible because of the second law.

The second law indicates that learning by imitation or instruction is impossible. Instead learning starts from within the brain by selectionist mechanisms (including trial and error) adjusted by prior knowledge and sense data as interpreted by the brain. Human beings have many inborn cognitive modules constraining this selectionist process making learning rapid. It is for example widely acknowledged that an inborn language module is required for language acquisition in children. Superimposed on this module, in my view, selectionist mechanisms are needed to fine-tune the sounds and meanings to the mother language. The different cognitive modules are products of Darwinian evolution (Tooby and Cosmides, 1992).

Due to the second law, any physical entity will in time disintegrate. No structure carrying knowledge can serve as template for lasting preservation of the knowledge. The only way to provide adaptations (knowledge) that outlast the corresponding physical entities seems to be by multiple copying. As long as the environment remains more or less unchanged, parallel copying of competing units (microstates) will preserve the knowledge represented by the units. Therefore, not only creation of knowledge, but also preservation of existing knowledge is dependent on "blind" variation, at least in the long run. Both preservation and creation of knowledge are entropy-producing processes far from equilibrium dependent on continuous supply of varying copies. Plato's dialogues would be unknown today if the ancient Greeks did not make many copies. Only laborious comparisons of different fragments of antique texts made the recreation of Plato's dialogues possible by monks in the Middle ages.

The second law is responsible for variations and if the number of copying errors exceeds the number that selection removes then adaptations are lost. Near exact copying is necessary for preservation of complex, adaptive novelties and this is dependent on discrete structures representing the adaptations.

The medium of storage and the copying mechanisms are much better for printed than for spoken stories. Printing allows knowledge to be physically tied by stable structures outside the brain. This explains why cultural evolution accelerated after the advent of literacy and especially after the invention of the printing machine. Cultural evolution is very limited in oral cultures due to the second law. Wherever there are adaptations, one should look for populations of competing, self-copying, discrete structures embodying information about the environment.

Conclusion

All information (knowledge, adaptations) is tied to physical systems. Knowledge represents macrostates to which different microstates (physical structures) correspond. The impossibility of instructionism is a simple manifestation of the second law. Selectionism, however, shows that search for novel, unpredictable knowledge is possible, and the second law constrains such searches to "entropy pumps" where populations of discrete, self-copying structures far from equilibrium compete to create low entropy adaptations at the expense of an overall increase in entropy. A better understanding of selectionist processes is important not least because of their impact on human and social development but also because the dominant theories outside biological evolution usually are instructionist. This article demonstrates that adaptive novelties in any domain are the result of selectionist mechanisms. As Layzer (1990, p. 307) states: ". . . . and [this new scientific worldview] assures us that there are no limits to what we and our descendants can hope to achieve and to become." There is a word for the act of producing adaptive novelties and that is creativity.

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