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SECOND CHANCES FOR LUCKY GAIA: A HYPOTHESIS OF SEQUENTIAL SELECTION

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James Lovelock's Gaia Theory proposes that the Earth and its life form a self-regulating system which keeps conditions favourable for life. One difficulty with this theory is how such a system could have originated - Richard Dawkins famously pointed out that natural selection between planets is impossible, and suggested that therefore planetary-scale properties could only arise by chance. Dawkins proposed that a destabilising system ("Anti-Gaia") would just as likely as Gaia, and would mean planetary extinction. Here we argue that the presence of life (with its capacity for death and evolution) enables a planet to explore different feedback systems in sequence, loading the dice in favour of the emergence of self-regulation.

The Gaia theory proposes that life and its physical and chemical environment on Earth form a self-regulating system that maintains a habitable state (Lenton, 1998; Lovelock, 1988; Lovelock & Margulis, 1974). However, since the properties of planets cannot evolve through natural selection within a competing population (Dawkins, 1983; Doolittle, 1981), how can regulatory behaviour arise at a planetary scale? Here we suggest that a cruder form of selection for regulation is able to operate on a series of systems over time, rather than on a population of systems co-existing at the same time.

Life exerts numerous influences on the physical and chemical environment through its role in biogeochemical cycles, the hydrological cycle and the planetary radiation budget (Steffen *et al.*, 2004). Biotic responses to changes in environmental conditions may therefore exert feedbacks on the environment. Such feedbacks may either dampen the initial perturbation (negative feedbacks) or enhance them (positive feedbacks). A planetary-scale life-environment system is likely to feature a large number of feedback mechanisms, both negative and positive, and clearly a key characteristic of the planet would be whether the net effect of its feedback mechanisms is to stabilise habitable conditions (regulation) or to destabilise them (anti-regulation). Some evidence suggests that the current Earth System is self-regulating, and a number of mechanisms have been proposed (Lenton, 1998). However, explaining the emergence of overall regulatory behaviour has remained a difficulty.

Although the many variants of the Daisyworld model (Watson & Lovelock, 1983) have demonstrated that, in principle, regulatory feedbacks can emerge from a system containing natural selection, this model relies on a direct connection between the selection of traits at the individual level and their planetary consequences (Lenton, 1998; Lenton & Wilkinson, 2003). In a cold climate, dark daisies warm their local environment and promote their own growth, and the aggregate effect of many dark daisies is an overall warming of the planet. If an individual dark daisy warmed the rest of the planet as much as it warmed its own local environment, light daisies would not be out-competed by dark daisies and regulation would break down.

In contrast, a number of regulatory mechanisms proposed for the real Earth involve the effects of organisms on the environment which are spread evenly across the globe and which therefore cannot be selected for on the basis of these global environmental consequences. For example, the temperature-dependent enhancement of rock weathering by vascular plants, mychorrizal fungi, lichens, and soil bacteria may regulate surface temperature by modifying the concentration of the greenhouse gas carbon dioxide (Schwartzman & Volk, 1989). Since CO_2 is well mixed in the atmosphere, an individual organism cannot preferentially modify the "greenhouse" forcing of its own local climate through enhanced rock weathering. Hence temperature regulation by rock weathering cannot evolve directly by natural selection (Lenton, 1998). So, while Daisyworld demonstrates in principle that Gaia and natural selection are compatible, it does not provide an explanation for the emergence of regulatory mechanisms that do not involve feedbacks on selection (Lenton, 1998).

If a planetary-scale feedback mechanism cannot have been naturally selected for, then the key process must be a by-product of selection at a much lower level (e.g. the gene) based on other factors. It has been argued, therefore, that the overall regulatory or anti-regulatory character of a life-bearing planet must also be a by-product, and if the Earth is self-regulatory then this is simply good fortune – Watson (1999) called this "Lucky Gaia". An anti-regulatory system could equally have emerged and driven itself to extinction (Dawkins, 1983). Taking this argument further, the anthropic principle has been invoked to "explain" our existence on a self-regulating planet (Watson, 1999). In contrast, we argue that the emergence of feedback mechanisms as by-products of natural selection does not imply that the ultimate emergence of planetary-scale regulation is purely a matter of chance. We suggest that, in the long-term, there should be a bias towards the ultimate emergence of a regulatory system.

Consider the case of an overall anti-regulatory system emerging as a by-product of evolution. Such a system may be termed "Anti-Gaia" (Dawkins, 1983). Previous arguments (Dawkins, 1983) have suggested that this must cause extinction of the biota resulting in a dead planet. However, in the case of Earth, we note that the physical and chemical environment is extremely heterogeneous. For example, local extremes of land surface temperature range from –89°C to 58°C, and local water availability ranges from zero to saturation. Some regions will therefore be closer to the limits of habitability than others. In a system driving itself away from optimum conditions, global-scale changes would lead to conditions becoming extreme in some locations before others. Extinction of life would not occur instantaneously across the globe, beginning earlier in some regions, while life in other regions continued. With life becoming sparse, the strength of the anti-regulatory mechanisms would diminish.

Ultimately, a point could be reached where some life still existed, but in a state too sparse to exert a significant impact on the global environment. At this point, "Anti-Gaia" would have driven itself out of existence. However, with life still persisting, albeit very sparsely, the planet itself is not dead.

Unless the planet had moved to a new stable equilibrium state, this removal of anti-regulatory processes would allow conditions to return towards those under which life previously evolved. As long as the planet remained habitable, the positive feedback inherent in reproduction would encourage the life in refugia to spread. Evolution would be unlikely to take the same pathway as that previously followed, so it would be possible for the biota to evolve properties different to those of the previous system. These could be either regulatory or anti-regulatory. If new anti-regulatory properties evolved, life would again approach extinction, "re-setting" the system and allowing evolution to explore yet another pathway. This would continue, either until regulation emerged or until the planet became subject to an extreme external forcing which left no refuges for life. Therefore, even if regulation can only emerge as a fortuitous by-product of evolution by natural selection, the biota could have a number of opportunities to evolve regulatory properties. Once emerged, a regulatory system would by its very nature be more likely to persist.

We note that continued evolution could ultimately result in the loss of the properties associated with regulation, so the regulatory system could merely be transitory. Nevertheless, the above mechanism increases the probability of a planet developing regulatory properties for some part of its history.

We contrast this with a planet whose physical and chemical environment is not affected by life. Abiotic feedback processes could also produce either regulation or anti-regulation (Holland, 1984), and if the feedbacks were anti-regulatory then the environment could be driven into a state unsuitable for life. However, in contrast to the biotic feedbacks that are removed when life becomes sparse, abiotic anti-regulatory feedback mechanisms would remain, rather than destroy themselves. Thus there is no opportunity to re-set the system. Furthermore, without evolution there is no mechanism for the generation of new, possibly regulatory properties.

This mechanism is similar to that previously proposed for the automated "learning" of stabilising behaviour by a mechanical system (Ashby, 1952). Instead of requiring conscious intervention or natural selection within a population of competing systems, self-regulation of a system can emerge through a mechanism that is effectively "trial and error". The presence of evolving life on a planet provides the system with two properties which are crucial to such a mechanism; (i) the capacity for death (and hence an ability to reset the system) and (ii) the capacity for change and hence the chance for new properties to emerge. A third crucial property, removal of one system whilst retaining the capacity for emergence of a new system, is provided by the inevitable heterogeneity of environmental conditions and hence the provision of refugia.

Such a mechanism was hinted at by the late, great Bill Hamilton, who in the context of Gaia sought "a *principle* concerning to why system-stabilising outcomes…are more likely than system-de-stabilising outcomes" (Hamilton, 1997a). He wrote: "I am hesitant myself as to whether when this set of principles is discovered it is going to involve n.s. {natural selection} in a big way or something else. I suspect one will be able to refer to n.s. but it won't be quite the idea as we normally think of it – vaguely I imagine that 'learning' through *repetitions over time alone* in a sufficiently complex system has to be shown able to replace the currently understood (and I am sure much more powerful) 'learning' through repetitions over both time and space, which is n.s. as we know it" (Hamilton, 1997a).

In conclusion, it has previously been argued that the presence of regulatory feedbacks on Earth could be pure good fortune (Doolittle, 1981; Watson, 1999), and we agree that this would be the case if the regulatory feedbacks were purely abiotic. However, the presence of life, with its capacity for death and mutation, endows a planet with special properties that increase the probability of regulation emerging. Evolving life introduces a mechanism for selection amongst a sequence of biotas, through which anti-regulatory outcomes can be eliminated and the eventual emergence of regulation becomes more probable. We therefore suggest that planets bearing life, including the Earth, could "evolve" self-regulatory properties through a process of sequential selection.

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