

Chapter 1

Dual phase evolution – a mechanism for self-organization in complex systems

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1.1. Introduction

A key challenge in complexity theory is to understand self-organization: how order emerges out of the interactions between elements within a system. Prigogine (1980) pointed out that in dissipative systems (open systems that exchange energy with their environment), order can increase. Rather than being suppressed, positive feedback allows local irregularities to grow into global features. Haken (1978) introduced the idea of an order parameter and pointed out that critical behaviour (e.g. the firing of a laser) always occurs at some predictable value of the parameter. Nevertheless, many questions remain, especially about the ways in which different processes act in concert with one another. In particular, the relationships between self-organization, natural selection and the evolution of complexity remain unclear.

Several of our recent studies (e.g. Green et al, 2000, Green & Sadedin 2005) imply that processes governing evolution in landscapes are similar to a wide range of phenomena that occur in vastly different contexts. Here we distil these observations into a single theory, which we term *dual phase evolution (DPE)*, and suggest that DPE may underlie self-organization in a many different systems.

1.2. Landscape phase changes and evolutionary learning

1.2.1. The role of catastrophes on different time scales

Our first indication that evolution in a landscape may represent a larger class of processes was the recognition of similarities in patterns and processes of biological change in landscapes on two scales.

On geological time scales, evolution occurs in fits and starts. There are long periods (tens or hundreds of millions of years) during which the flora and fauna of a region remain largely constant, forming the main geological periods. The transition from one period to the next is usually very abrupt. In 1980 Alvarez et al. provided evidence that the Cretaceous-Tertiary boundary was associated with impact of a large asteroid [Alvarez et al. 1980]. Subsequent research found evidence for asteroid impacts, volcanic activity and climate change associated with other geological boundaries.

Examination of patterns of species turnover showed that these boundaries were also associated with mass extinction events. This led Eldredge and Gould (1972) to propose their punctuated equilibrium hypothesis. They argued that instead of proceeding at a steady pace, evolution occurred mainly during brief bursts of diversification. These bursts were preceded by mass extinctions, and followed by long periods of stasis. Eldredge and Gould suggested that mass extinctions release evolutionary constraints by providing empty ecological niches and decreased competition. As new species evolve and populations grow and spread, competition increases. Consequently, the opportunity for evolutionary novelty declines until a steady state is reached which is ultimately broken by a large external perturbation such as an asteroid strike (Fig. 1).

The causes of punctuated equilibrium in the fossil record are still disputed. In this debate, one key observation has been largely neglected. This observation is that similar patterns of change also occur on much shorter time scales. An excellent analogue for punctuated equilibrium is found in vegetation history during the last 10,000 years.

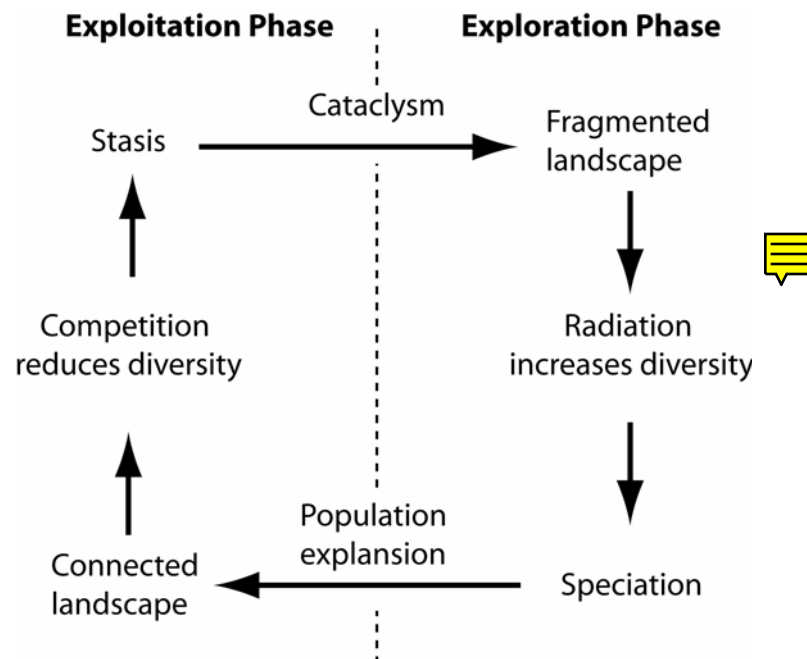


Figure 1. Diagrammatic representation of the dual phase nature of species evolution.

1.2.2. Holocene forest history

An early triumph of Quaternary palynology was to demonstrate that vegetation changes during postglacial times followed consistent patterns over vast regions of Europe and North America. A crucial element in this work was that just like the geological record, pollen histories show that forest changes occur abruptly, in fits and starts.

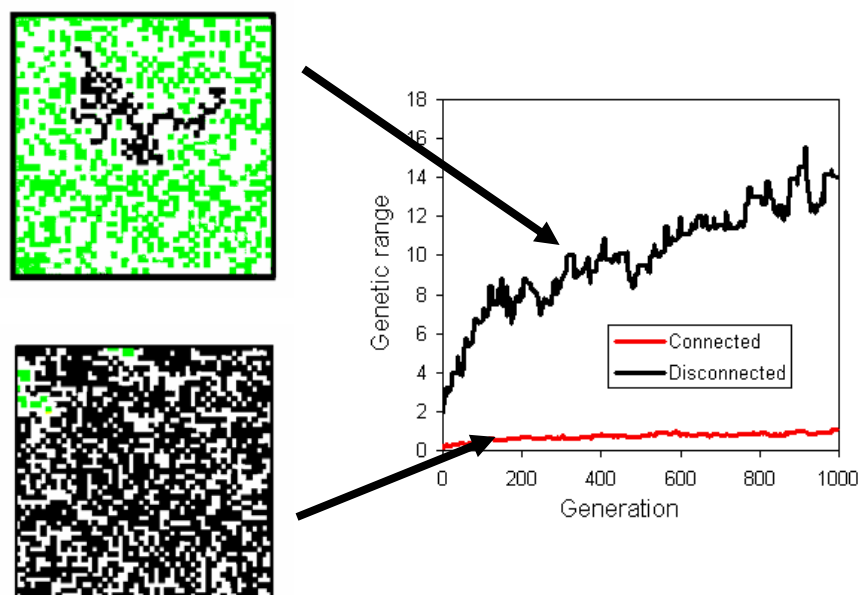
Palynologists divide vegetation histories into “pollen zones”, which are periods of relatively homogeneous pollen composition. As with geological periods, transitions between pollen zones mark rapid, major shifts in species composition. The zones are periods of stability, punctuated by sudden phase shifts triggered by major environmental disturbances, usually forest fires (Green, 1990). The parallels between vegetation change and evolution are striking: pollen zones correspond to geological eras, sudden changes in community composition correspond to mass extinctions, and major fires correspond to asteroid impacts.

The above correspondences suggest that some common process underlies both evolution and forest change (Green, 1994). Simulation studies (see below) suggest that biotic interactions within landscapes are responsible. In the case of forest change seed dispersal acts as a conservative process (Green, 1989). Because they possess an overwhelming majority of seed sources, established species are able to out compete invaders. By clearing large regions, major fires enable invaders to compete with established species on more equitable terms. Conversely seed dispersal also enables rare species to form clumped distributions that allow them to survive in the face of superior competitors. This mechanism appears to be important for the maintenance of diversity in tropical rainforests (Green, 1989).

Figure 2. Simulated genetic drift in a landscape. Connected areas (examples shown in black) are small when the density of patches is sub-critical (top), but occupy the entire region when the density is super-critical. The graph at right shows the course of random genetic drift under these two cases. In a connected landscape, breeding suppresses genetic divergence, but in a fragmented landscape, random drift quickly leads to evolutionary divergence.

1.2.3. Landscapes, cataclysms and connectivity

Phase changes in the connectivity of a landscape can potentially explain both



punctuated equilibrium and pollen zones.

A fundamental feature of landscapes is that sites in a landscape can be connected with respect to processes that occur within them. In evolution and ecology, this means that individuals can migrate between sites, and consequently processes that are occurring in one site can spread to others.. This property gives rise to the potential for a phase change in the connectivity of the landscape as a whole when the density of connected sites crosses a critical threshold. Above the threshold, the landscape is overwhelmingly connected and feedback processes that occur in one region can rapidly percolate throughout the environment. Below the threshold, the landscape fragments into isolated, independently evolving patches (Fig. 2).

Cataclysms such as fires, asteroid strikes or volcanic activity can drastically alter the connectivity of the landscape, flipping it from a connected to a disconnected state or vice versa. After a cataclysm, the landscape is largely empty. Surviving populations occupy isolated refugia, and are consequently fragmented. At geological timescales, ecological depletion and spatial fragmentation create ideal conditions for adaptive radiation. At finer timescales, they allow for the explosive spread of previously suppressed minorities. As the landscape fills, it passes the critical threshold once again and spatial suppression inhibits innovation. In this way, phase changes in landscapes may explain both punctuated equilibrium and pollen zones.

The evolutionary impact of landscape phase changes can be seen in cellular automata models (Fig. 2). When the density of habitat patches exceeds the critical level, they merge into a single connected region. This means that there is a single breeding population, and random genetic drift is suppressed (Figure 2). However, when the density of patches is sub-critical, the landscape becomes fragmented into separate patches and a population breaks up into isolated sub-populations. Under these conditions, genetic drift is unconstrained and speciation becomes likely (Fig. 2).

1.2.4. Natural processes

We can also see the above process, or elements of it, at work in a variety of different natural phenomena. Firstly, it occurs in landscape ecology on time scales much shorter than postglacial forest history. For instance, off the coast of California the kelp beds have a stable mix of plant species. However every few years a major storm rips through the ecosystem, which afterwards can reform with a completely different mixture of species (Dayton et al. 1984). There are also many ecosystems where external forces impose landscape phase changes. In central Australia, for instance, rainfall mediates phase changes in the distribution of water birds (Roshier et al. 2001). During wet years, the landscape is essentially connected. The birds can fly virtually anywhere by moving from one water body to another. However, in drought years, most water bodies dry up, and the landscape becomes fragmented, confining the birds to small isolated areas.

Implicit in the mechanism proposed above are two processes – variation and refinement – that occur in many other contexts. In learning and development, for example, Piaget proposed two processes – *accommodation* and *assimilation* – that correspond to the above phases. Accommodation occurs when a child encounters a novel situation and needs to find a new pattern of behavior, a new “schema”, to deal with it. Assimilation occurs when a child encounters a variation on a known situation and assimilates the experience by adapting an existing schema to deal with it.



1.2.5. Optimization algorithms

Many adaptive algorithms used in optimization apply phase changes implicitly to mediate between global search (*exploration*) and local search (*exploitation*). Fitness landscapes provide a convenient basis for understanding why this is so.

In a fitness landscape, we imagine all the potential solutions to a problem laid out on a pseudo-landscape, with values of key parameters fixing location and the object function (“fitness”) defining the elevation. In the Great Deluge Algorithm, for instance, a random walker can initially wander anywhere within the fitness landscape, even areas of low elevation (ie. poor solutions). In other words, global search operates. However, rising “flood” waters make the areas of low elevation inaccessible. At first, this is not a problem for the walker, who can skirt around the pools of water, and all elevated areas remain connected. However, when the water level reaches a critical point, connectivity in the landscape breaks down and the walker becomes trapped on a single hill. From that point on, the walker is confined to local search (i.e. hill-climbing).

Other optimization algorithms exploit phase changes in other ways. In simulated annealing, for instance, the cooling schedule plays the role of rising flood water.

1.3. Dual phase evolution

1.3.1. The theory

Based on the above observations, we argue that evolution within landscapes exemplifies a family of mechanisms that differs from other widely known phenomena, such as self-organized criticality. In essence, our research suggests that underlying self-organization and emergence in many complex systems is a mechanism that incorporates:

1. State spaces possess dual phases, with variation (exploration) dominant in one phase and selection (exploitation) dominant in the other.
2. Complexity accumulates as a result of repeated phase changes.
3. Phase changes are mediated by perturbations.
4. After perturbation, low connectivity decouples the dynamics of many local patches, allowing chaos to act as a source of novelty (exploration phase)
5. The system becomes increasingly connected over time.
6. When connectivity rises above the threshold, unstable interactions and poorly-adapted designs are selected out, allowing increasingly complex, stable and orderly structures to crystallize (exploitation phase).

1.3.2. Relationship to other forms of critical behavior

Dual phase evolution (DPE) differs in important ways from other processes that involve critical behavior. In particular, the theory of self-organized criticality (Bak et al., 1987, 1988) deals with processes that drive a system to approach a critical state and remain there. In contrast, DPE deals with systems that normally lie well away from a critical state, but are occasionally driven across a critical threshold by external disturbances. The two theories describe different aspects of critical behaviour and are complementary.



Several authors have suggested that self-organized criticality may explain punctuated equilibrium if evolution drives ecosystems towards a critical state where a tiny perturbation can initiate an avalanche of extinctions. However, most mass extinctions seem to be associated with a large external perturbation rather than being self-organized, and therefore seem closer to the DPE model than to self-organized criticality. In addition, models of self-organized criticality suggest that it requires rather finely-tuned parameter values that are unlikely to arise by chance (but see Halley et al. 2004). DPE is not incompatible with self-organized criticality, but it offers a potentially more robust mechanism for punctuated equilibrium.

The present theory also differs from the “edge of chaos” model, which arose from studies into the behaviour of automata, with the relevant critical region lying within an automaton’s state space. There is a phase change, from simple to chaotic, which occurs in automata with increasing richness of behavior. Automata that lie close to this “edge of chaos” often display the most interesting behavior, including universal computation. This observation led to speculation that only automata whose state spaces lie within this critical region possess important properties, such as universal computation and the ability to evolve (Langton, 1990).

Rather than settling in the critical region, the phenomena we describe here exhibit jumps through the critical region. They do not settle and remain in a critical state. More generally, the two models were developed to describe different things. In contrast the model developed here derives from considerations of system structure, such as the connectivity within a landscape.

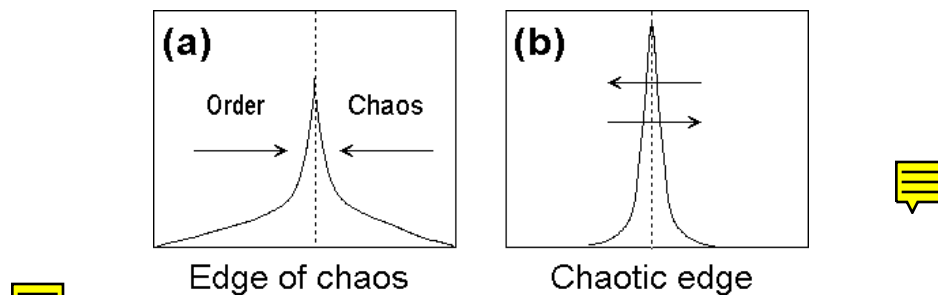


Figure 3. Contrasting the edge-of-chaos and phase-shift models of evolution in complex systems. The x-axis represents a connectivity “order” parameter appropriate to the system concerned. The spike represents the critical point where a phase change occurs. (a) In the edge-of-chaos model complex systems evolve to lie near or at the critical point (the spike) between ordered and chaotic phases. (b) In the phase shift model, which is described here, external stimuli flip the system across the chaotic edge into the phase where variation predominates. The system then gradually returns, crystallizing into a new structure or behaviour as it does so. See the text for further explanation.

1.4. An application

We have successfully exploited DPE to improve the performance of genetic algorithms. In the cellular genetic algorithm (CGA), for instance, we mapped the agent population

onto a pseudo landscape (not a fitness landscape), allowing breeding only with neighbors (Kirley & Green 2000). We introduced intermittent phase changes in landscape connectivity by including cataclysms that cleared patches

These steps made it possible for the algorithm to maintain a diversity of solutions and avoid premature convergence, a common problem with genetic algorithms. The intermittent “disasters” introduced phase changes between connected and fragmented landscapes. The effect of disturbance was to allow “fitter” solutions to expand. In other words, the disturbances mediated regular swaps between local and global search.

1.5. Conclusions

The theory of dual phase evolution that we have outlined here proposes that many systems develop and change by a mechanism involving phase changes. Left to themselves such systems will rapidly evolve to a stable state where selection refines existing adaptations, but creativity is limited. However external events may disturb the system, flipping it into a different phase in which variation, rather than selection, dominates. The phase transition is an essentially chaotic phenomenon that perturbs the systems in unpredictable ways, and thereby acts as a source of novelty. Following the phase change the system gradually drifts back into its original phase, but settles into a completely new, and often more complex, steady state.

A crucial unresolved question is how genuine novelty accumulates in complex systems. Some theorists, such as Walter Freeman, have suggested that in some contexts life exploits chaos as a source of novelty (Freeman, 1975). Freeman found that, in the brain, similar stimuli could evoke widely different patterns of response.

References

- Alvarez, L.W., Alvarez, W., Asaro, F. and Michel, H.V., 1980. Extraterrestrial Cause for the Cretaceous-Tertiary extinction. *Science* 208, 1095-1108.
- Bak, P., Tang, C. & Wiesenfeld, K. Self-organized criticality. An explanation of 1/f noise. *Phys. Rev. Lett.* 59, 381–384 (1987).
- Bak, P., Tang, C. & Wiesenfeld, K. Self-organized criticality. *Phys. Rev. A* 38, 364–374 (1988).
- Bransden, T. & Green, D.G., 2005. Getting along with your neighbours - emergent cooperation in networks of adaptive agents, in *Workshop on Intelligent & Evolutionary Systems (IES2005)*, edited by Ohuchi, A., Suzuki, K., Gen, M. and Green, D.G. Future University-Hakodate, Japan. <http://www.waseda.jp/sem-genlab/~IES2005/>
- Cornforth, D., Green, D.G. & Awburn, J., 2005. The formation of hierarchical structures in a pseudo-spatial co-evolutionary artificial life environment. In *Recent Advances in Artificial Life, Advances in Natural Computation*, vol. 3 (eds.), edited by Abbass, H.A., Bossomaier, T.R.J. & Wiles, J.. World Scientific (London), 55-68.
- Conner, P.K., Currie, V., Gerrodette, T., Keller, B.D., Rosenthal, R., & Ven Tresca, D., 1984, Patch dynamics and stability of some California kelp communities, *Ecological Monographs* 54(3), 253-289.
- Eldredge, N. and Gould, S.J. 1972. Punctuated equilibria: An alternative to phyletic gradualism. In T. J. M. Schopf, ed. *Models in Paleobiology*. Freeman, Cooper, San Francisco. pp. 82–115.
- Freeman, W.J., 1992. Tutorial on neurobiology: from single neurons to brain chaos. *International Journal of Bifurcation and Chaos* 2(3), 451-482.

- Green, D.G. & Bransden, T.G., 2006. Complexity theory. In *McGraw-Hill Encyclopedia of Science and Technology*. McGraw-Hill (New York). pp. 507-511.
- Green, D.G. & Bransden, T.G., 2006. Complexity theory. In *McGraw-Hill Yearbook of Science and Technology*. McGraw-Hill (New York). pp. 65-67.
- Green, D.G., Leishman, T.G. & Sadedin, S. 2006. The emergence of social consensus in simulation studies with Boolean networks. *World Congress on Social Simulation (WCSS06)*, Kyoto University (Kyoto).
- Green, D.G., 2004. *The Serendipity Machine*. Allen and Unwin (Sydney).
- Green, D.G., 2003. Self-organization in networks. in *Proceedings of 2003 Asia Pacific Symposium on Intelligent and Evolutionary Systems: Technology and Applications*, edited by M. Gen, A. Namatame, O. Katai, R. McKay, H.S. Hwang, and B. Liu. Waseda University (Tokyo) (ISBN 0731705033) pp 10-14.
- Green, D.G., 2001. Hierarchy, complexity and agent based models. In *Our Fragile World: Challenges and Opportunities for Sustainable Development*. UNESCO (Paris), 1273-1292.
- Green, D.G., and Kirley, M.G. 2000. Adaptation, diversity and spatial patterns. *International Journal of Knowledge-Based Intelligent Engineering Systems* 4(3):184-190.
- Green, D.G., 2000. Self-Organization in complex systems. In: *Complex Systems*. T.J. Bossomaier and D.G. Green (Editors), Cambridge University Press, pp. 7-41.
- Green, D.G., Newth, D and Kirley, M. (2000) Connectivity and catastrophe - towards a general theory of evolution. In M.A. Bedau et al. (eds.) *Artificial Life VII: Proceedings of the Seventh International Conference*. pp 153-161. MIT Press.
- Haken, H., 1978. *Synergetics*. Springer-Verlag, Berlin.
- Halley, J.D., Warden, A. C., Sadedin, S. and Li, W. 2004. Rapid self-organized criticality: Fractal evolution in extreme environments. *Physical Review E*, 036118.
- Harvey I., and Bossomaier T.R.J., 1997. Time Out of Joint: Attractors in Asynchronous Boolean Networks, *Proc. Fourth European Conference Artificial Life*. ed. P. Husbands and Harvey I., p67-75, 67-75.
- Heng, T.N. and Green, D.G. 2004. *VLAB - The Artificial Life Laboratory Online*. <http://www.complexity.org.au/vlab/>
- Holland, J.H., 1995. *Hidden Order: How Adaptation Builds Complexity*. Addison-Wesley, New York.
- Kauffman S. A., 1991. Antichaos and adaptation, *Scientific American* 265(2), 64-70.
- Kirley, M., and Green, D.G. 2000. An Empirical Investigation of Optimisation in Dynamic Environments Using the Cellular Genetic Algorithm. In D. Whitley et al. (eds) *The Proceedings of Genetic and Evolutionary Computation Conference (GECCO-2000)*. pp. 11-18. Morgan Kauffman.
- Langton, C.G. (1990). Computation at the edge of chaos: phase transitions and emergent computation, *Physica D* 42(1-3), 12-37.
- Langton, C.G. (1992). Life on the edge of chaos, in *Artificial Life II*, Addison-Wesley, New York pp. 41-91.
- Prigogine, I., 1980. *From Being to Becoming*. W. H. Freeman and Co, San Francisco.
- Roshier, D.A., Robertson, A.I., Kingsford, R.T. and Green, D.G. 2001. Continental-scale interactions with temporary resources may explain the paradox of large populations of desert waterbirds in Australia. *Landscape Ecology* 16, 547-556.