

Chapter 1

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

David G. Green, Tania G. Leishman¹ and Suzanne Sadedin
Clayton School of Information Technology
Monash University, Clayton 3800, Australia
david.green@infotech.monash.edu.au

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.

The results from 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 many 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 Formerly Tania Bransden

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 came when we detected similarities between the patterns and processes of biological change in landscapes on two completely different 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 comet [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. The causes of punctuated equilibrium in the fossil record are still disputed. However, a key observation has been largely neglected. It 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.

1.2.2. Holocene forest history

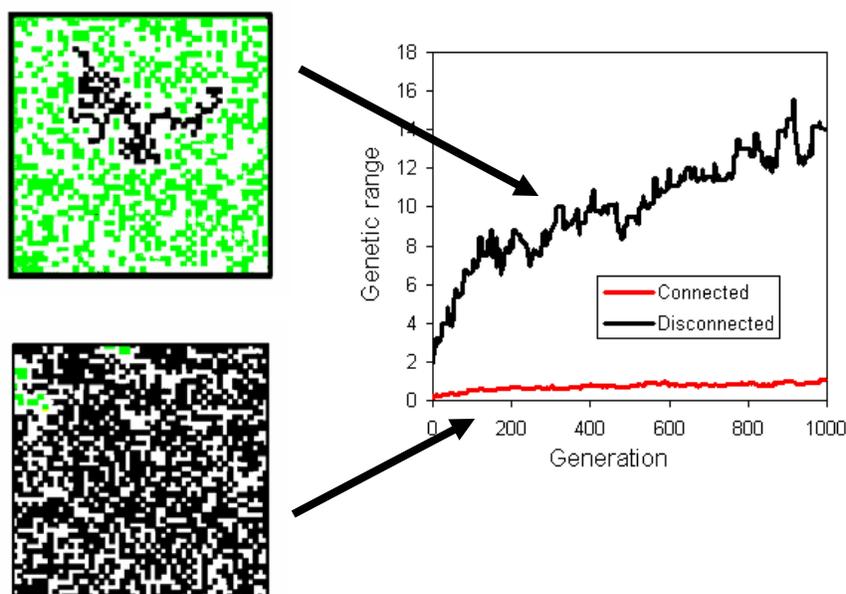
An early triumph of Quaternary palynology (the study of preserved pollen) was to show that vegetation changes during postglacial times followed consistent patterns over vast regions of Europe and North America. Pollen histories also show that forest changes occur abruptly, in fits and starts, just like evolution in the geological record.

Palynologists divide vegetation histories into “pollen zones”, which are periods of relatively constant pollen composition. Transitions between pollen zones mark rapid, major shifts in species composition. Like geological periods, zones are punctuated by sudden phase shifts that are triggered by disturbances, usually forest fires [Green 1990].

Pollen zone transitions differ drastically from the normal process of ecological succession and cannot be explained by the *Intermediate Disturbance Hypothesis* (IDH). The IDH (Connell & Slatyer 1977) postulates that diversity is maximized in ecosystems that suffer occasional local disturbances which allow both competitors and colonizers to coexist indefinitely at large scales. Thus the IDH refers to transient local dynamics, whereas the pollen zone transitions mark permanent large-scale changes in forest composition.

The parallels between vegetation change and evolution are striking: pollen zones correspond to geological eras, changes in community composition correspond to mass extinctions, and major fires correspond to asteroid impacts. This correspondence suggests that a common process underlies both evolution and forest change [Green & Kirley 2000]. Simulation studies (see below) suggest that biotic interactions within landscapes are responsible, with seed dispersal acting as a conservative process [Green

1989]. Because they possess an overwhelming majority of seed sources, established species are able to exclude competitively superior invaders. By clearing large regions, major fires enable invaders to compete with established species on equal 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

Figure 1. Simulated genetic drift in a landscape. Connected areas at left (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 equilibria and pollen zones. Sites in a landscape are connected by processes, such as dispersal, that involve movement from place to place. 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. If density exceeds the threshold, the landscape is overwhelmingly connected and feedback processes that occur in one region can rapidly percolate throughout the environment. If density is subcritical, the landscape fragments into isolated, independently evolving patches (Fig. 1).

Cataclysms such as fires, asteroid impacts 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 populations. 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 [Green et al. 2000].

The evolutionary impact of landscape phase changes can be seen in cellular automata models (Fig. 1). 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 (Fig. 1). 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. 1).

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. 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 sometimes 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. 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.

In the above examples, the biological implications of the phase changes are not clear, however, environmental phase changes of the kind we discussed above have been implicated in the evolution of at least one group of species: the cichlid fishes found in the lakes of Africa [Sturmbauer & Meyer 1992]. Here the phases are mediated by lake levels. Adaptive radiation and speciation predominate when water levels are high, whereas the environment is fragmented during phases of low water levels, so competition, selection and extinction predominate [Kornfield & Smith 2000].

Implicit in the mechanism proposed above are two processes – *variation* and *refinement* – that occur in many contexts. In learning and development, for example, Jean Piaget proposed two processes – *accommodation* and *assimilation* – that correspond to the above phases [Block 1982]. 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.

The issue of learning leads naturally to questions of brain function. Several studies raise the possibility of phase changes being involved in brain function. Most notably, Freeman [1975, 1992] showed that living neural systems are prone to respond chaotically. He found that even slight differences in stimuli could evoke widely different patterns of neural response. More recently, it has been suggested [Yevin 2006]

that phase changes between subcritical and supercritical brain states may mediate human sleep-wake patterns and creative behavior.

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 (i.e. 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 incorporate phase changes in different ways. In simulated annealing, for instance, the cooling schedule plays the role of rising flood water by imposing increasing restrictions on variations to parameter values.

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 differ 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 (*Dual Phase Evolution*) that incorporates the following (Fig. 2):

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

To begin, we argue that DPE explains how punctuated equilibrium arises. Eldredge & Gould [1972] argue for two evolutionary phases: here we suggest that spatial connectivity provides a mechanism for evolutionary phase changes. Moreover, the

mechanisms involved in DPE indicate that the proliferation of new species after mass extinction can arise in several ways, especially the expansion of existing but previously rare species, and unleashing genetic variation by spatial fragmentation and ecological depletion. Finally, by linking the mechanism to a variety other processes, such as forest ecology, we have shown that punctuated equilibrium is a special case of DPE.

DPE differs in important ways from other processes that involve critical behavior. In particular, the theory of self-organized criticality [Bak et al. 1987] 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 external stimuli occasionally drive them across a critical threshold. The two theories describe different aspects of critical behavior and are complementary.

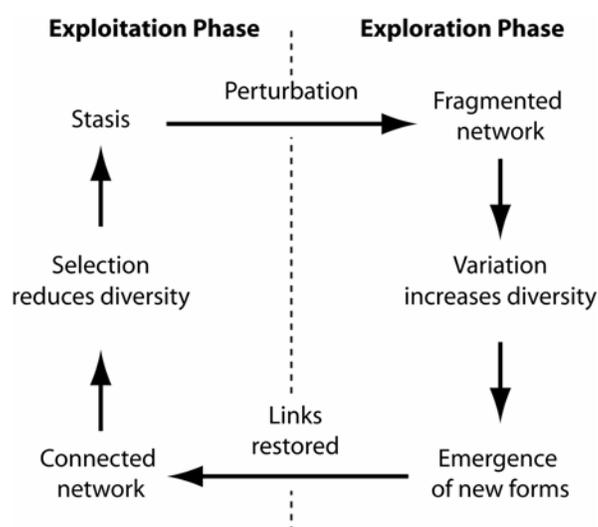


Figure 2. Generic representation of the processes involved in dual phase evolution.

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 [Langton 1990]. Rather than settling in the critical region, the phenomena we describe

here exhibit jumps through the critical region. They do not settle in a critical state and remain there. Numerous authors [e.g. Freeman 1975; Langton 1990] have suggested that chaos provides a source of novelty in nature. In the cases we describe, one phase is essentially chaotic. So such systems acquire novelty while in the “exploration” phase.

1.3.3. 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.

The theory of dual phase evolution raises many new questions to be answered. What role does it play in structural change within networks? What kinds of emergent features arise via DPE? Can DPE contribute to encapsulation and module formation? [e.g. Holland 1995]. We have also raised the possibility that DPE plays a role in many different contexts, such as learning, brain function, macroevolution, ecological phase transitions and adaptive problem solving. These ideas have yet to be explored more carefully. Finally, there still remains a need to identify clear criteria for identifying conditions where DPE is active.

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