

Expanding Evolutionary Theory Beyond Darwinism with Elaborating, Self-Organizing, and Fractionating Complex Evolutionary Systems

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ABSTRACT

Earth systems increase in complexity, diversity, and interconnectedness with time, driven by tectonic/solar energy that keeps the systems far from equilibrium. The evolution of Earth systems is facilitated by three evolutionary mechanisms: *elaboration*, *fractionation*, and *self-organization*, that share universality features not found in more familiar equilibrium systems. These features include: 1. evolution to sensitive dependent critical states, 2. avalanches of changes following power law distributions with fractal organization, and 3. dynamic behaviour as strange attractors that often exhibit bi-stable behaviour. We propose a new approach to teaching Earth systems theory, where theoretical underpinnings of evolutionary mechanisms are introduced, followed by explorations of how the mechanisms interact to integrate the lithosphere, atmosphere, hydrosphere, and biosphere into a unitary evolutionary system. We incorporate conceptual and computer-based interactive models (included here as educational resources) within our lesson plans that illustrate a hierarchy of principles and experimental outcomes for evolutionary mechanisms. Application of this educational framework requires explicating complex systems mechanisms and their interactions, exploring their applicability to Earth systems, and imbedding them in high school as well as college introductory and upper level Earth Science classrooms to put all Earth systems on a comprehensive, integrated, universal evolutionary theoretical foundation.

INTRODUCTION

Ask the average person, "What is the theory of evolution?" and you are likely to get answers like "natural selection", or "survival of the fittest", or "Darwin's theory." Because these ideas are systematically taught in classrooms, they may represent the only evolutionary theory people know. But, ask, "What is the theory of Earth evolution?" you will likely get a blank stare, or at best a superficial discussion of the fossil record. The Earth as a multi-faceted evolutionary system that undergoes continuous change through time was incorporated in the National Science Education Standards, even if it is absent from many contemporary curricula and common perceptions (see Figure 1).

In this manuscript, we propose that an expanded definition of evolution be applied both in teaching and research to fully explicate the understanding of Earth systems. Such an expanded definition—explicating the different evolutionary processes within each domain of lithosphere, atmosphere, hydrosphere, as well as biosphere as well as how evolutionary processes in one sphere affects the other spheres—will support a much richer understanding of the complexity of Earth systems. A companion paper (Fichter, Pyle, Whitmeyer, 2010) explores strategies and rubrics for teaching evolutionary dynamics as chaos/complex systems.

EXPLORATION

Biological evolution is commonly taught in terms of changes in the gene pool of a population from generation to generation by such processes as mutation, natural selection, and genetic drift as organisms adapt to changing environments. However, we do not teach the evolution of Earth systems (geosphere, atmosphere, hydrosphere) through any similar sort of connective or transformative process. We may speak of the theory of plate tectonics, or describe the breakup of Pangaea, but these are usually taught as descriptive stories rather than as analytical theories following specific principles resulting in evolutionary outcomes that connect and integrate all Earth systems. As a result, many Earth science concepts are presented as discrete ideas, without connection to any central, universal, unifying theoretical framework for understanding, such as evolutionary theory serves for biology.

Another part of the problem is that, although we teach the behavior of physical and chemical systems in terms of energy (gravitational, thermal, electrical, etc.) we also teach these systems as decaying to closed, equilibrium states. If the 2nd law of thermodynamics is correct, and all systems descend directly to higher entropy, then how is any evolution possible? In order to answer this question, one must accept that all the Earth systems (geosphere,

NSES Content Standard D.9-12.B stipulates:

1. ...The early Earth was very different from the planet we live on today.
2. Geologic time can be estimated by observing rock sequences and using fossils to correlate the sequences at various locations. Current methods include using the known decay rates of radioactive isotopes present in rocks to measure the time since the rock was formed.
3. Interactions among the solid Earth, the oceans, the atmosphere, and organisms have resulted in the ongoing evolution of the Earth system. We can observe some changes such as earthquakes and volcanic eruptions on a human time scale, but many processes such as mountain building and plate movements take place over hundreds of millions of years. (NRC, 1996, p.189).

FIGURE 1. NSES Content Standard D.9-12.B

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atmosphere, hydrosphere, biosphere) are actually open systems, continuously driven to far-from-equilibrium states by the ongoing dissipation of tectonic and solar energy resulting in evolutionary change through time. An earthquake zone, for example, does not close down after

an earthquake. Rather the zone exists as a system continuously dissipating energy from the Earth's interior. Because of differential friction along the zone, the energy cannot be dissipated uniformly or smoothly.

Instead, the zone self-organizes its stress patterns until friction is locally overcome, leading to a quick pulse of energy release, followed by stress building to criticality in a different region where it becomes sensitive dependent to the next energy release (Bak, 1999, Jensen, 1998, Hergarten 2002). Similarly, along a subduction zone, volcanoes do not erupt continuously, but a volcanic eruption coming to an end does not mean the whole system has wound down to equilibrium, like a ball coming to rest at the bottom of a bowl, because the volcano is not an isolated system. The Earth is a heat engine and as eruption follows eruption not only do the volcanoes dissipate the Earth's internal energy, but rocks composing the volcano evolve, the subduction zone evolves, the ocean basin evolves, and along with these volcanic eruptions the atmosphere and hydrosphere evolve.

Ilya Prigogine, who won the 1977 Nobel Prize for his theory of non-equilibrium dissipative structures states:

"In the world that we are familiar with, equilibrium is a rare and precarious state." (1984, p 128). "Equilibrium structures can be seen as the results of statistical compensation for the activity of microscopic elements (molecules and atoms). By definition they are inert at the global level. For this reason they are also "immortal." Once they have been formed, they may be isolated and maintained indefinitely without further interaction with their environment. When we examine a biological cell or a city, however, the situation is quite different: not only are these systems open, but also they exist only because they are open. They feed on the flux of matter and energy coming to them from the outside world. We can isolate a crystal, but cities and cells die when cut off from their environment. They form an integral part of the world from which they draw sustenance, and they cannot be separated from the fluxes that they incessantly transform."

The Earth will, of course, eventually become a closed system when its tectonic and solar energy is all used up some billions of years in the future, but along the way a great deal of complexity, diversity, and organization in all the Earth systems will continue to evolve. On geologically long time scales (millions to billions of years) Earth systems are clearly evolutionary, and adaptive. Here we define adaptation broadly as an internal change in a system that mirrors an external event in the system's environment (Flake, 2000). The atmosphere at 4.0 Ga was about 95% CO₂, but evolved through a methane-rich phase to a nitrogen-oxygen rich phase (Kasting, 2004). Meanwhile, the lithosphere evolved from a state with no continents, to small proto-continents, to large continents, to cycles of supercontinents (Condie, 1997; Rogers and Santosh, 2004). Simultaneously, as life—and the evolving Earth environments life has fostered—has evolved the abundance and diversity of minerals have expanded from about 250 minerals typical of a proto-planetary body to the approximately 4400 minerals present today (Hazen, et

al. 2008, Hazen 2010). The composition of the rocks that compose the lithosphere have also systematically evolved through geologic history (e.g. increasing production of granite, Windley, 1995, with specific rocks always being generated and found in specific tectonic locations (Fichter, 1996). It is these mineral and rock responses in part that give the Earth sciences their predictive power.

Clearly an evolutionary theory using physical/chemical analogues for genes, mutations, and natural selection will not work to explain these Earth evolutionary changes. Nor can we argue that evolution as a process properly belongs only to biology, or that all transformative changes must be couched in terms of how biology theorizes those changes. The idea that many kinds of systems undergo transformative evolution change is universal. For example, the titles of these currently available books: "Evolution of the Social Contract" (Skyrms, 1996), "The Evolution of Cooperation" (Axelrod, 2006), "The Origins of Wealth: Evolution, Complexity and the Radical Remaking of Economics" (Beinhocker, 2007), "The Evolution of Human Language" (Larson, et al., 2010), "The Evolution of Culture" (White, 2007), and "The Origin and Evolution of the Universe" (Zuckerman, 1996). The mechanisms of evolution posited by biology are not transferable to the evolutionary changes these books are talking about. But, in science it is not proper to have a theory without specific, logical, rational, and testable mechanisms of how that change takes place, mechanisms that go beyond ad hoc explanations and "Just So" stories.

Darwinism, however, is not the only mechanism of evolution. If we define evolutionary change as any process that leads to increases in complexity, diversity, order, and/or interconnectedness then there are at least three distinct mechanisms, or theories of evolution: *elaboration*, *self-organization*, and *fractionation*.

Elaborating Evolutionary Processes

Elaborating evolution begins with a seed, an ancestor, or a randomly generated population of agents (individual interacting units, like birds in a flock, sand grains in a ripple, or individual units of friction along a fault zone), and evolves by generating, and randomly mutating, a large diversity of descendants which are evaluated by an external fitness function; those that do not measure up are selected out. The fitness function may be a real environment, an abstract environment, or another "species" of agents. The result is increases in diversity, complexity, and abundance with time—through multiple generations—due to adaptation to ever changing environments.

Elaborating evolution is characterized by experimentation—lots of experimentation; and failure—lots of failure. Indeed, failure is one of the key components of natural selection. Ninety-nine percent of all species that have ever existed are extinct and most individuals born do not survive to reproduce. Yet the diversity and abundance of life continues to expand. By the middle Ordovician (~470 Ma) about 400 families of animals had evolved; today the number is about 1900 families (Sepkoski, 1984). Yet most of the families that existed in the Ordovician are

extinct. To maintain this natural selection machine, life has to continuously elaborate, constantly produce new genotypes to experiment with.

But, biology is not the only example of elaborating evolution. Businesses, for example, behave similarly to living systems as they diversify in an elaborating economy (Beinhocker, 2007), and on average 10% of businesses fail-go extinct-every year (Ormerod, 2007). Indeed, the precise mathematical relationship that describes the link between frequency and size of the extinction of companies is virtually identical to that which describes the extinction of biological species in the fossil record (Ormerod, 2007). Cultural ideas ("memes," Dawkins, 1979) are also elaborating evolutionary systems.

But, because the units of biological evolution (genes, individuals, species, etc.) are not common to all elaborating evolutionary systems, Darwinian evolutionary theory is not a general theory of evolution, but a special case of elaborating evolution. What is common to all elaborating evolutionary systems is the General Evolutionary Algorithm: 1) differentiate, 2) select, 3) amplify, 4) repeat (Beinhocker, 2007). Any system that evolves by this process, regardless of the actual units that are differentiating and being selected, is an elaborating evolutionary system. Resource #1 lists a variety of computer-based models of General Evolutionary Algorithms (a.k.a. genetic algorithms), and Fichter and Baedke (2010) provide online resources, experimental models, and classroom demonstrations.

Conversely, we teach biological adaptation so pervasively in terms of Darwinian mechanisms that we might not be aware that not all biological evolutionary adaptation is explainable by gene changes. For example, the first few hits in a Google search of "evolution", including the Wikipedia site, discuss evolution only in terms of biology and gene changes. But, a family group or an ecosystem is organized not because of gene changes, but because of self-organizing positive/negative feedbacks among the individuals and between the individuals and the environment (e.g. Lotka-Volterra predator-prey models, and Daisyworld models, Watson & Lovelock, 1983). Individual adaptations to changing food supplies, temperatures, or other environmental variables are often physiological adaptations, not genetic ones. Conversely, there is not a gene to code for every stripe and spot in a shell or animal pelt, or every capillary in a circulatory system. Since chemical/physical (e.g. oscillating chemical reactions - Resource #2) and mathematical (cellular automata - Resource #2) systems can also evolve patterns analogous to these biological patterns, and since the chemical/physical systems are not under genetic control, it follows that direct genetic control is not a necessary requirement for the production of these patterns. These patterns and organizations evolve by a different mechanism: self-organization.

Self-Organizing Evolutionary Processes

Self-organizing evolution begins with an initial state of random agents that through the application of simple rules of interaction among the agents (e.g. an algorithm, or chemical/physical laws) evolves a system of ordered

structures, patterns, and/or connections without control or guidance by an external agent or process. That is, the system pulls itself up by its own boot straps—a.k.a. Local Rules leads to Global Behavior .

Self-organizing processes are widespread, common, and diverse, and technically belong to the realms of chaos (Gleick, 1988) and complex systems theories (e.g. Waldrop, 1992; Johnson, 2002; Solé, 2002; Strogatz, 2004; among others). Chris Lucas (2006), for example, says, "complexity theory states that critically interacting components *self-organize* (emphasis added) to form potentially evolving structures exhibiting a hierarchy of emergent system properties." This results in a potential source of confusion in that most descriptions of complex systems theory describe them as self-organizing, as if the only way complex systems can behave is by self-organization. But, elaborating biological systems are also complex systems, as are fractionating systems (see Fichter, Pyle, Whitmeyer, 2010 for descriptions of the differences between chaos and complex systems theories). What characterizes a system as a complex system is not the mechanism of evolutionary change, but the fact they all possess the same universality properties (e.g. fractal, sensitive dependence, timing and strength of events following a power law, etc.).

Theoretically, self-organizing systems are modeled by a variety of mathematical models, including: Self-Organized Criticality (Bak, 1999; Jensen, 1998; Hergarten 2002), cellular automata, genetic algorithms, autocatalytic networks (Kauffman, 1993, 1996), and oscillating chemical reactions (Prigogine, 1984). Self-organization is common in growth and development processes (Goodwin, 2001), phylotaxis in plants, development of social and ecological networks (Epstein and Axtell, 1996), and the functioning of biochemical pathways. Self-organizing theories are used to explain how networks evolve (from the World Wide Web to social networks, to ecosystems, Barabasi, 2003); how ants without central leadership build a colony that looks like it has design and purpose (Resnick, 1994); turbulence in fluids, cross bedding in sediments (Forrest and Haff, 1992), river drainage patterns, evolution of earthquake systems, crystal growth, growth of urban sprawl, patterns in animal pelts and shells, the shape of spiral galaxies, and a host of others. Ball (2001) gives a wide array of examples from many disciplines. Flake (2000) explicates the computational algorithms for a variety of self-organizing systems. Resource #2 lists a sampling of self-organizing systems, and Fichter and Baedke (2010) provide online resources, including downloadable, interactive computer models or applets for experimentation and class room demonstration.

Evolution and Extinction: It is interesting that biology has developed elaborate theories and mechanisms for how evolution occurs, but that these do not incorporate equally powerful theories and mechanisms for extinction. In the mechanisms of elaborating evolution extinction seems incidental to the process—just unfortunate accidents. Part of the difficulty is that elaborating mechanisms do not lend themselves to explaining a process that is superficially the antithesis of evolution. But, then again,

extinction is usually the province of paleontology, which has the data base to see extinction's patterns. Yet, of the several dozen books that explore extinction, most deal with specific causes for specific extinctions rather than explicating a universal theoretical model of extinction. Self-organizing mechanisms (Self-Organized Criticality in particular; see Bak, 1999), on the other hand, incorporate as part of their normal dynamics periodic avalanches (sudden, dramatic breakdowns of the system, like extinctions.) This is a case where complex systems theories of evolution provide a natural and logically inevitable explanation for widely observed and universal processes which heretofore have been inexplicable. In this situation, elaborating evolution—the ongoing spewing off of new species—is imbedded within a larger self-organizing evolutionary process where ecosystems build to a critical state from which they inevitably collapse (avalanche)—go extinct.

Two central questions that concern extinction are: 1) are mass extinctions qualitatively different from background extinctions, and 2) are extinctions the result of endogenous causes (within the community or ecosystem itself), or exogenous causes (a perturbation in the environment that changes the stress levels to the point species go extinct). Empirically we have not been able to find universal answers with any confidence. Raup (1992), presents a dialectical exploration of these questions, with a fascinating argument-counter argument on whether all large extinctions are caused by asteroid impacts. Raup's arguments are rooted in a statistical exploration of random walks and how we can reason from a theoretical analysis of random processes to understanding extinctions. In a similar vein others are beginning with theoretical principles of self-organized criticality and reasoning to an understanding of extinction from there. These are based on the observation that extinction, rather than being a normally distributed random process, follows a power law distribution (small extinctions are frequent, but have little effect; large extinctions are rare but result in dramatic changes.) Power law distributions are one of the universality properties of complex systems and any universal theory of evolution and extinction must incorporate these complex systems ideas.

Newman (1997) surveys the early work on the role of self-organized criticality for understanding extinctions. Newman also presents a model of pure exogenous causes that match Sepkoski's (1984) data on Phanerozoic extinctions. Conversely, Sole' and Manrubia (1996) have developed a complex systems model that also reproduces Sepkoski's data relying on purely endogenous mechanisms. These seemingly contradictory results have opened new ways of thinking about extinctions as complex systems that naturally build to critical states that are sensitive dependent to collapse from a wide diversity of shocks. Sometimes large extinctions are precipitated by small shocks, and large shocks do not necessarily result in large extinctions. The methods of these studies cannot be summarized here, but Ormerod (2007) provides a concise summary, evaluation, and discussion of the implications for both biology and economics.

Fractionating Evolutionary Processes

Fractionating evolution begins with a complex parent which is physically or chemically divided into fractions through the addition of sufficient energy because of differences in the size, weight, valence, reactivity, etc. of the component particles. Because fractionating systems follow chemical/physical laws, it is possible to predict (calculate) the evolutionary path of the system, and its end state. In this way fractionating systems differ from elaborating and self-organizing systems whose evolutionary trajectories are unpredictable and deductively unknowable.

A simple example of fraction; a slight breeze or slight static electric charge is sufficient to separate pepper flakes from a salt and pepper mixture, leaving the resultant mixture enriched in salt and the winnowed fraction enriched in pepper. A fractionating system is adaptive because it is adapting to changing chemical/physical conditions. Evolution of Earth materials is mostly a fractionation process, including the compositional evolution of the atmosphere and oceans, and the evolution of rocks (conversely the development of rock fabric is most likely self-organizing). For example, igneous rock evolution begins with a chemically complex parent that in hand specimen resembles a basalt. Through successive stages of partial melting the initial rock is divided into fractions, an unmelted fraction that is more mafic than the parent, and a melted fraction that is more felsic than the parent. A simplified fractionation sequence is: a mafic basalt generates an intermediate diorite, which generates a felsic granite. Fractionation mechanisms usually lie in the realm of the laws of physics and chemistry, but biological processes can also fractionate, such as the fractionation of carbon isotopes in shells. Biological processes are also integral links in the biogeochemical fractionation cycling of elements like carbon, oxygen, and sulfur, and the long-term evolution of the Earth's atmosphere, as well as the evolution of the Earth's minerals (Hazen et al. 2008, Hazen, 2010).

Many of the more common systems on Earth evolve by fractionation, including each major rock type, as well as the atmosphere and hydrosphere. An important implication of this is that the circular rock cycle so commonly taught in Earth science classes as an equilibrium system, leaves out a most important component—that the geological Earth is an evolutionary rock cycle, and has undergone directional and irreversible change with time (i.e. is a fractionating system evolving toward known ends) (Fichter, 1966; 1999; Rollinson, 2007; Whitmeyer, Fichter, & Pyle, 2007). Unlike the standard circular rock cycle the evolutionary rock cycle associates specific rocks with specific tectonic locations making a direct connection between tectonics and fractionating evolutionary processes, a step toward building a complete, encompassing evolutionary theory of the Earth. The tectonic rock cycle is not circular but is open, representing the evolution inherent in the processes. Fractionation evolution is thus as important for introductory geology students to understand as Darwinian evolution is important for introductory biology students to understand. Dobzhansky (1973) said,

“Nothing in biology makes sense except in the light of (biological) evolution.” Likewise, nothing in geology makes sense except in light of fractionating and self-organizing evolution.

Because fractionation as a process is pervasive in natural systems, and is a widespread and well understood industrial process (e.g. fractionation of petroleum, and purification of almost any thing you can imagine), scientists have developed analytical and sophisticated models for these systems. Fractionation is not a mystery.

On the other hand, we are unaware of any experimental models or computer based experimental programs that explore principles of fractionating evolution as a complex system, either in the spirit of the General Evolutionary Algorithm for elaborating evolution, or comparable to the many specific self-organizing evolutionary algorithms. That is, a model with simple rules that can be tuned to explore how different conditions result in different outcomes. The one exception to this might be oscillating reactions that result in fractionation, but we include these as self-organizing systems (although this does indicate that although the three evolutionary mechanisms can operate alone, they commonly overlap and work together.)

CONCLUSIONS

So, to return to the question posed at the beginning of the paper: “What is the theory of Earth evolution?” In fact, there is more than one, just like there is more than one mechanism by which biological systems increase in complexity, diversity, order, and/or interconnectedness. There are three theories/mechanisms of evolutionary change and all are responsible for the Earth’s evolution. Because the mechanisms inherent in these three theories are common, widespread, and have many examples, it is important that all be explored in teaching how the natural world works. Thus, when we speak of Earth *systems*, what we mean is that each of these complex evolutionary processes is simultaneous and intertwined with each of the others, feeding into and out of the others in a kaleidoscope of evolving patterns that is the world all around us.

The interactions exist at all scales of observation (that is, they are fractal). Within the biosphere, for example, there are individuals, species, biomes, etc. all interacting in complex ways. To approach Earth systems from a complex systems viewpoint what we are interested in is how the evolutionary processes in one sphere influences the evolutionary processes in another sphere. Thus, if we are interested in any system that evolves then we are driven to expand our interest and understanding to include all evolutionary processes occurring on Earth. For example, the fractionating evolution of atmospheric gasses over geologic time has been largely mediated by biological processes, but not all fractionations are biological (e.g. fractionation of oxygen isotopes, and most, but not all, mineral fractionations). Conversely, over short geologic time scales (e.g. thousands of years), elaborating evolutionary change has little influence on how fractionation occurs, but at longer geological time scales the evolution of biological elaboration mechanisms has

changed the way that chemical fractionation occurs. Then again, the fractionating evolution of the atmosphere has at times changed opportunities for elaborating evolution and subsequently the long-term evolution of life on Earth, e.g. appearance of oxygen in the early Proterozoic, and the precipitous decline of oxygen at the end of the Permian (Huey and Ward, 2005). A whole new paradigm of Earth science education based on complex evolutionary systems lies in front of us.

A chaos/complex systems perspective of evolution is not a replacement for the current theories of evolution we have, it is an enhancer. By looking at evolution through the mathematics and universality principles of chaos/complex systems theories we will see new dimensions and new possibilities that might not have occurred to us before. For a discussion of strategies, rubrics, and learning outcomes for teaching these complex evolutionary systems see Fichter, Pyle, and Whitmeyer 2010.

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- Web links to these resources available at Fichter and Baedke (2010):
- Resource #1: Elaborating Evolution**
- The theoretical world of non-biological elaborating evolution is mostly contained in the field of Artificial Life (a.k.a Alife), actually a branch of mathematics. An excellent introduction to the subject is Levy (1993), but the world wide web has many sites devoted to the many facets of the subject. Search under artificial life, genetic algorithms, cellular automata, and robotics. The beauty of Alife studies is the ability to create electronic bugs and place them in electronic ecosystems and watch them evolve. These are called genetic algorithms. On the other hand, the behavior of some Alife systems can be explained verbally with great effect. The suggestions below are only a small sampling of what is available.
- WordEvolv** - The idea for WordEvol comes from a DOS based computer program by Stephen Prata (1993), rewritten by Steve Baedke in a Windows version. A very effective demonstration of how efficiently a mutation/natural selection strategy can evolve a meaningful pattern from a meaningless string of random letters.
- > Fichter and Baedke, 2010
- John Muir Trail** - This genetic algorithm was developed by an MIT research group to discover how efficiently an electronic species could learn to run a trail. It is described by Levy (1993) and Johnson (2002), and we use it to explain the principles of a genetic algorithm.
- > An online more technical description by Jefferson, Collins, and Cooper is found at: <http://www.cs.ucla.edu/~dyer/Papers/AlifeTracker/Alife91Jefferson.html>
- Avida and Tierra** - In these two programs a population of self-replicating computer programs is subjected to external pressures (such as mutations and limited resources) and allowed to evolve subject to natural selection. These systems are as close as we have gotten so far to life in a computer. Avida is the research version, Tierra created by Tom Ray provides downloadable software. As with the John Muir Trail the procedures and outcomes are readily accessible and understandable, and can be easily described.
- Avida**: <http://portal.acm.org/citation.cfm?id=992860>
Tierra: <http://life.ou.edu/tierra/>

Sim Life (as well as **Sim Ant**, **Sim City**, and **Sim Earth**) are not just computer games, they are all genetic algorithms that evolve through interactions with the player. The brain child of Will Wright, they evolved out of his early interest in robotics and system dynamics. If you or your students are familiar with these "games" then you have first hand experience with a genetic algorithm.

Floys - these are available as applets on the WWW. Floys belongs to the realm of flocking Alife systems (called boids). The basic version is only a flocking system and thus belongs technically a self-organizing system, but there is available at the same site a version that evolves as a genetic algorithm.

> <http://www.aridolan.com/ofiles/JavaFloys.html>

Resource #2: Self-Organizing Evolution

For as diverse and sometimes complex as self-organizing theories are, self-organization can be easily explained and demonstrated with computer models. A vast and rapidly growing literature on these theories exists, ranging from qualitative explanations to highly mathematical explorations. A search of the WWW or books on Amazon.com on self-organization reveals a plethora of resources. Below are several resources that introduce these ideas at a level accessible to almost anyone.

Self-organized Criticality (SOC) - Per Bak (1999) and colleagues modeled the SOC theory as a sandpile, and then applied it to a wide variety of other systems. The metaphor of the behavior of a sandpile is a very effective description of self-organized criticality. Wikipedia also has a nice explanation of SOC. Jensen (1998) provides a mathematical exploration.

Boids - were originally developed by Craig Reynolds (2001) in 1986 to demonstrate the simple rules of flocking and schooling behavior. Since then dozens of flocking programs have been written, many available for free download from the WWW.

> Reynolds web site (<http://www.red3d.com/cwr/boids/>) is a compendium of papers and programs.

MatFa's Boids (available at Fichter and Baedke, 2010)

Cool School (<http://www.kewlschool.com/>) Cool School simulates a school of fish and predators using behavioural modeling. A real-time three-dimensional rendering of the simulation is displayed, and the user can interactively adjust the parameters of the behaviour models.

JavaAnts (<http://www.mcrit.com/Complexity/applets/boid.html>)

Floys (<http://www.aridolan.com/ofiles/JavaFloys.html>).

Cellular Automata - consist of a grid of cells whose states change (or remain the same) depending on simple rules dependent of the states of their neighbors. Visually these are some of the most effective examples of self-organization. Levy (1993) gives a basic introduction, but most of the literature is highly mathematical. Cellular automata are widely used as a research tool in disciplines as diverse as physics, chemistry, biology, sociology, anthropology, and others. Many free downloadable computer versions are available. A simple introduction and description of cellular automata can be found at the web site:

> **Life3000** available at (Fichter and Baedke, 2010). This is one of the earliest, simplest, and easiest to use

cellular automata written by David Bunnell. This is the one we have our students experiment and play with. A series of experiments using this program are also available at the web address. The program allows one of the simplest demonstrations of self-organization; use the mouse to swirl an array of random cells with at least 200 live cells and let it run. After varying times of activity the system will self-organize into simple static or oscillating groups of live cells, and it will do so every time regardless of the starting state.

> **Life32** (<http://psoup.math.wisc.edu/Life32.html>). A free downloadable CA that is flexible, powerful, and adaptable.

> **Mirek's Celebration** or **Mcell** (<http://www.mirekw.com/ca/download.html>). A very nice free downloadable CA that comes with hundreds of files demonstrating different behaviors CA are capable of. In particular look at the "Must See" folder.

> **MJ cell** - an applet version is at <http://psoup.math.wisc.edu/mcell/mjcell/mjcell.html>.

Diffusion Limited Aggregate (DLA) - a DLA is a fractal growth model that demonstrates how a random process following very simple rules can produce self-organized patterns.

> <http://apricot.polyu.edu.hk/~lam/dla/dla.html>

Oscillating Chemical Reactions (reaction-diffusion and activator-inhibitor; also sometimes called chemical clocks)

The Belousov-Zhabotinsky reaction is a spatio-temporal chemical oscillator. Discovered by Boris P. Belousov in 1951 his paper on the reaction was rejected as being impossible. Later in 1961, a graduate student named A. M. Zhabotinsky rediscovered this reaction sequence. These now fall in the realm of oscillating chemical reactions, including reaction diffusion and activator inhibitor systems (Prigogine, 1984, and Ball, 2001). Downloadable programs are:

> Five Cellular Automata: <http://www.hermetic.ch/pca/pca.htm>

> Ilya.exe: <http://www.fssc.demon.co.uk/rdiffusion/ilya.htm>

> Texture Garden Reaction Diffusion: <http://texturegarden.com/java/rd/>

Resource #3: Fractionating Evolution

We are unaware of any computer based experimental programs that explore principles of fractionating evolution, either in the spirit of the General Evolutionary Algorithm for elaborating evolution, or comparable to the many specific self-organizing evolutionary algorithms. A representative version of the fractionation of a magma can be found at Karl Wirth's course materials page at:

<http://www.macalester.edu/geology/wirth/wirth.html>. These activities (simple and complex) use M&Ms or similar colored candies to represent the ions present that make up common igneous rock forming minerals.