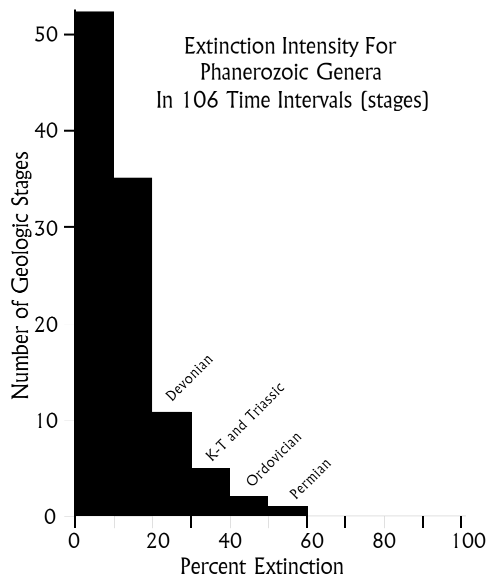
BAK-SNEPPEN MODEL OF EVOLUTION

Bak, Per and Kim Sneppen, 1993, Punctuated Equilibrium and Criticality
in a Simple Model of Evolution: Physical Review Letters, Vol. 71, No. 24, p 4083-4086
Programmed by Steve Baedke; Documentation by Lynn S. Fichter

The Scientific Argument That Led to the Model

From the time of Darwin and to the present day, gradualism has been the basis of all modern biological theories of evolution. ***Gradualism*** argues that evolution takes place by slow, steady changes over long periods of time. Biologists, who study evolution over geologically short time spans (years to hundreds of years), using population genetics to study gene frequency changes, see gradualistic evolution in their experiments.

In 1972, however, paleontologists Niles Eldredge and Steven Jay Gould argued that the fossil record, where we observe changes over long time spans (tens of thousands to billions of years), shows ***punctuated equilibrium***: *equilibrium*, stasis, or no change—*punctuated* by short intervals of very fast change. Punctuated events were further supported by David Raup's observations (1992) that extinctions follow a power law distribution—small events are common and insignificant, large events are rare and significant—plotting as a straight line on a log graph, or alternatively like the curve to the right. That is, extinction is fractal—a signature of self-organized-critical systems.



Note that the number of large extinctions, like the Permian, are very infrequent, occurring only in one geological stage, while smaller extinctions— <10 %—occurred in over 50 separate geological stages.

The debate between gradualism and punctuated equilibrium was extremely contentious during the 1970's and 1980's; at one scientific meeting punches were thrown by the antagonists. This controversy has begun to die down a little; each side has declared victory, and gone on about their business—meaning the debate remains unresolved. For the most part biologists and paleontologists are still not meaningfully talking with each other about evolution.

The Bak-Sneppen Model

Per Bak and Kim Sneppen developed their evolutionary model in the early 1990's to test the punctuated equilibrium observations made by Eldredge, Gould, and Raup. Since both punctuated equilibrium and power-law extinctions are similar to the sand pile behavior that Bak studied, the Bak-Sneppen (B-S) model was designed to see if a stripped down computer based evolutionary model could be designed that would self-organize to a critical state, and exhibit avalanche behavior that follows a power law distribution. If it did that would support punctuated evolution.

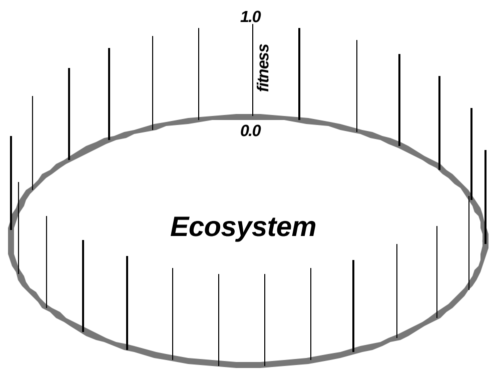
The B-S evolutionary model is an "ecosystem" in which the fitness of each "species" changes because of its relationships with other "species", following two simple rules.

Rule One **-** find the species with the lowest fitness and randomly change its fitness. *When a species has low fitness almost any change is beneficial, but because we do not want to build in a rule that will increase fitness independent of the model's dynamics we just change fitness at random..*

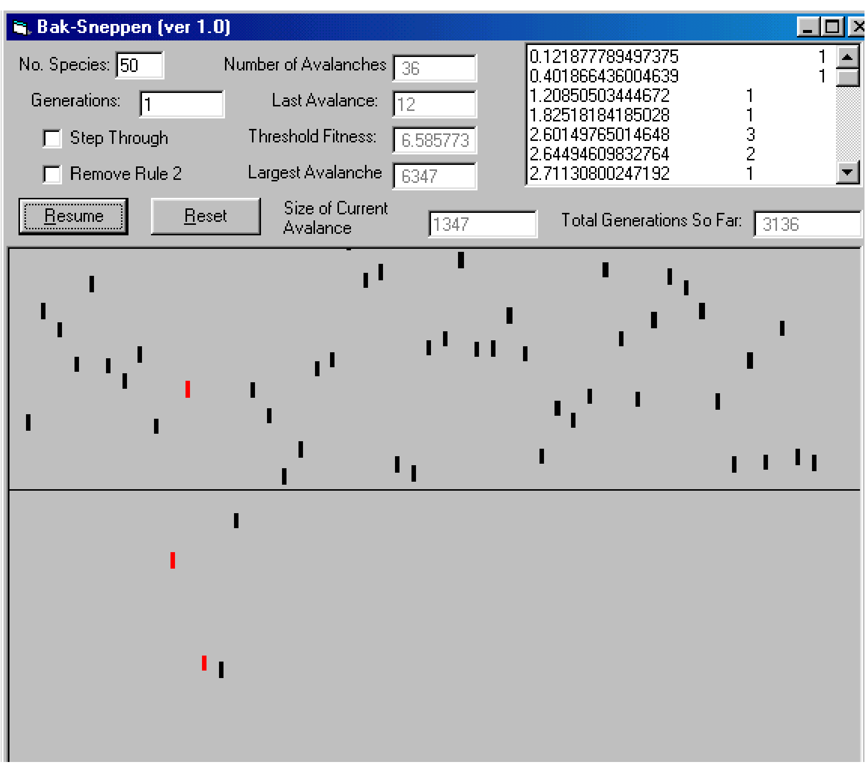
Rule Two - at the same time the lowest fit species is changed, also randomly change the fitness of the species to the immediate left and right. *Species do not exist in isolation; they are always part of a community. Therefore, a change in one species changes the fitness of the species it interacts with, in this case the ones to the right and left. And, again, fitness changes at random to not build bias into the model.*

The model parameters include the following:

1. The model contains some number of species, usually 50-200, each represented only by its total fitness, a number ranging from 0.0 (extinction) to 1.0 (maximum fitness).
2. Visually, each species is represented by a vertical line. The higher the fitness the longer the line, up to maximum fitness (length = 1.0). Only a dot marking the top of the fitness line is visible in the computer simulation; with full lines it is harder to see what is happening.
3. The species fitness lines are laid out side-by-side in a row (see screen capture below), but the row end wraps; that is, an event that moves off the left side appears on the right side, and vice versa. Imagine it as a circle of vertical lines (like to the right), and the entire circle represents the "ecosystem."



4. The acting out of Rules One and Two are seen as flurries of dots blinking on and off, scattered at first, but later concentrating in zones about 10 to 20 species wide. These are the tops of the fitness lines changing length as fitness changes.



5. ***Threshold fitness*** is the highest level the lowest fitness has reached to date in the model's run. Threshold fitness in the model is shown by a horizontal line that rises with time, although flurries of activity drop below this line with each avalanche.
6. An ***avalanche*** is the cascade of fitness changes below the threshold (i.e. all the blinking dots below the line), although this behavior also results in random fitness changes above the line. An avalanche begins as soon as any species' fitness drops below the threshold, and lasts as long as any activity remains below the threshold. The length of the avalanche is the number of mutations that occur between the beginning of the avalanche and the threshold fitness being exceeded again. The end of an avalanche results in the threshold line rising to a new lowest fitness.

Applications and Implications

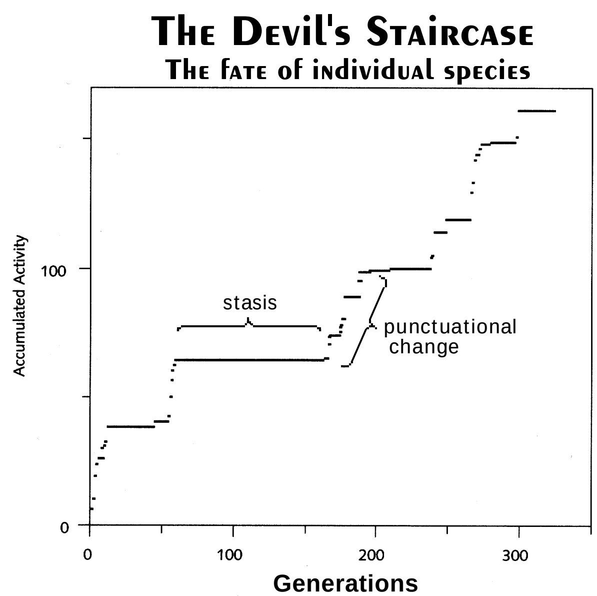
Does any interesting behavior arise from such a simple system, especially behavior that mimics biological behavior? We do not expect random processes to produce an organized outcome; random events should remain, well, random—unorganized. Organization takes purpose, design, or at least causes that have a preferential (deterministic) direction. And, there is no natural selection here to drive the system.

What the B-S model illustrates is that even random processes can result in self-organization to a critical state. Threshold fitness rises, rapidly at first, then exponentially slows until it reaches about 0.66, the critical state–from which level extinction avalanches sweep back and forth through the ecosystem.

None of the changes observed in the system are *designed*, however, to increase the critical threshold or lead to extinction avalanches, but the dynamics of the model lead inevitably to self organized criticality. A change in one species is analogous to dropping a grain of sand onto the sand pile; sometimes one grain causes an avalanche, sometimes it takes a lot of grains to build to the next threshold, and another avalanche. The avalanches follow a power-law distribution.

Punctuated Equilibrium

Punctuated equilibrium in the B-S model is seen in the Devil's Staircase plot to the right. The Devil's staircase shows the accumulated activity of one species undergoing a series of evolutionary changes. Horizontal lines are times of stasis when fitness is not changing. Vertical jumps are punctuated mutations; note these come in bundles (multiple avalanches) over short time intervals. In reality there are many more mutation steps in each bundle than the graph can show. One can think of the number of changes as representing the amount of physical change in the animal, such as size. The "punctuated equilibrium" nature of the curve is evident in the long times of stasis followed by jumps in activity.



Power-Law Extinctions

At the critical point (~ 0.66) avalanches sweep back and forth through the ecosystem (see Activity Pattern graph on the last page "Dynamics of the Bak-Sneppen Evolutionary Model"). Periodically even stable species get swept up in an avalanche, and go extinct, only to be replaced by another species with different fitness.

The deeper significance of extinction avalanches is that the extinctions have no identifiable cause. Yes, just one random mutation below the threshold sets off the extinction avalanche. But, that is just the point—it is random, with no identifiable cause. Just one of many minor changes. The result is an avalanche of extinctions and new species generation that may go on for just a few generations, or millions of generations before the avalanche is over.

We are always looking for the cause of an extinction, the smoking gun that killed off all those species. But extinctions are not necessarily caused by some external event, such as an asteroid impact or a dramatic climatic change. Such events may, of course destabilize a critical system enough to precipitate an extinction, but the B-S model implies that such external events are not necessary. A real system not at the critical state may experience an external trigger without it precipitating an avalanche, while a system at the critical state is sensitive dependent enough it may experience an avalanche even without an external trigger. The trigger may simply be the flap of the butterfly wing—the extinction of a single species—that results in an avalanche that propagates through the entire system. Extinction is inherent just within the dynamics of evolution.

Personal Implications

In his book "How Nature Works" Bak explains the implications of self-organized criticality this way.

> *There is not much that an individual can do to protect him/herself from these disasters. Fate plays a decisive role for the sandpile inhabitant. It is the criticality that makes life complicated, and the accidents of where you live. The sandpile theory - self organized criticality - is irresistible as metaphor The formation of a person's identity is analogous to the formation of the sand pile. A personality reaches the critical state; then the impact of each new experience reverberates throughout the whole person, both directly, and indirectly, by setting the stage for future change. Because these changes are subject to sensitive dependence each person's history and personality is unique.*

This leads to a couple of questions. Imagine that the B-S model is a society, with those having higher fitness being higher on the social/wealth ladder, and those with low fitness, or caught up in an avalanche (say a war), being poor, less fortunate souls. What are the implications of the Bak-Sneppen model for these questions?

1. Watch the ***individuals above the threshold***. How stable are they?
   - How much do they ***contribute*** to raising the threshold line to the next level?
   - Can you think of anyone, or any group, in our society analogous to the "people" above the threshold?

2. Get personal. Pick out ***one individual*** above the threshold line ***and identify with it***; imagine it is you.
   - How ***safe*** are you in this avalanche prone world?
   - How much ***control*** do you have over your destiny?
   - Are there any ***innocent victims*** in this society?
   - Is there any way to ***protect*** yourself in such a world?

3. Is there any part of this ecosystem that is ***isolated*** from the rest, sitting in a ***protected niche, independent and self sufficient?***

Stuart Kauffman once said,

The critical point is not a "nice place to be."

Yes, but it is the place we live, and in fact the only place we can be.