

Lakes Victoria and Malawi as well as to *Astatoreochromis alluaudi*. The results confirm (with 97 per cent confidence) the hypothesis, suggested by interspecific hybridization studies, that *A. burtoni* is a closer relative of these flocks than is *Astatoreochromis*. This analysis also suggests (although not significant statistically) that *A. burtoni* is closer phylogenetically to the Lake Victoria flock than is the Lake Malawi flock.

Furthermore, and contrary to the hypothesis of Crapon de Caprona and Fritzsich above, the members of the Lake Victoria flock (including *A. nubilis*, *A. elegans* and *A. piceatus* are more closely related to one another mitochondrially than to *A. burtoni*. The bootstrap value that shows the reality of the a-b lineage in the figure is 100 per cent. We infer that the Lake Victoria flock arose long after the splitting of the *A. burtoni* lineage from the a-b lineage. Our molecular estimate of the time of most recent common ancestry for the Lake Victoria flock is 200,000 years¹, which implies that the flock is younger than the lake (250,000 to 750,000 years old⁶). Thus, our results cast doubt on Crapon de Caprona and Fritzsich's model, above, according to which segregation occurred within the flock before the lake formed.

Another notable feature of the figure is

'Life' not critical?

SIR — Bak *et al.*¹ have presented evidence that the cellular automaton, the 'game of life', develops into a self-organized critical state², characterized by a $D(T) \sim T^{-1.6}$ distribution of times T required for the lattice to return to equilibrium following a random single-site perturbation. This power law implies an infinite expected equilibration time $\langle T \rangle$. But we believe that this behaviour is an artefact resulting from the relatively small lattices (100 by 100) used in ref. 1.

Self-organized criticality describes situations in which a spatially extended dissipative system spontaneously adjusts itself, without deliberate tuning of any external parameter, into a state with no finite correlation length or relaxation time, like an equilibrium statistical-mechanical system at its critical point. In a classic example², the addition of sand grains one at a time to an idealized sandpile increases the slope until a critical slope is reached, after which the arrival of an additional grain is likely to trigger an avalanche of any size, up to the size of the entire system, maintaining the mean slope thereafter at the critical value. A general mechanism of such criticality has been elucidated for models having a conserved quantity, such as the amount of sand. But Bak *et al.* suggest¹ that systems that lack any evident conserved quantity may also be critical.

On a finite $L \times L$ lattice, large avalanches are not possible, and the expected equilibration time $\langle T \rangle$ implied by the $T^{-1.6}$ power law is no longer infinite but should increase with L at least as $L^{0.4}$, because the initial per-

turbation can increase in diameter at most linearly with time. Our studies on lattices up to $1,024 \times 1,024$ with periodic boundary conditions (Fig. 1a) show instead that $\langle T \rangle$ approaches a constant value 200 ± 10 for lattices larger than about 100×100 . This suggests a characteristic extinction length of ~ 50 lattice points for perturbations propagating outward from their point of origin.

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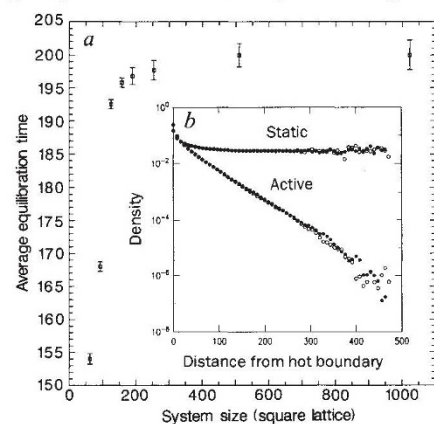


Fig. 1a, Average decay time for point perturbations in the game of life, as a function of linear system size, for square arrays with periodic boundary conditions. Perturbations decaying in ≤ 6 steps are excluded from the average. b, Semi-logarithmic plot of static and active density as a function of distance from the hot boundary, in a 488×256 array with a hot boundary on the left, a free boundary on the right and periodic boundary conditions in the vertical direction. Dots and circles show results of two independent runs of about 30 million steps each.

To determine this extinction length more precisely, we measured active and static densities (see below) in other runs (Fig. 1b) as a function of distance from an inhomogeneous 'hot' boundary, in which the configuration was randomized every 16 steps. The static density approached a characteristic equilibrium value of 0.03 away from the boundary, whereas the active density (here defined as live sites that were not alive 6 steps previously) declined exponentially with a scale length of 42 ± 3 , indicating a uniform rate of extinction per unit distance for perturbations propagating away from the hot boundary.

Our results indicate that the game of life is subcritical, with a large but finite relaxation time of 200 ± 10 steps and an extinction length of 42 ± 3 lattice points, and that the equilibrium state, restored after the decay of perturbations, is a roughly spatially uniform distribution of decoupled local oscillators with a density of ~ 0.03 . The possibility remains, however, that this apparent equilibrium may be metastable with respect to nucleation events too rare to have occurred in any of our simulations so far. This would be the case, for example, if the game of life allowed the existence of configurations analogous to Belousov-Zhabotinsky spiral cores, which cannot be destroyed from outside but instead entrain their surroundings in coherent waves of minimum period⁴.

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