

Earthquakes in the Brain

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The amazing quantity of information required to initialize the enormous number of connections on which is based the neuron network functioning cannot possibly be encoded in the genoma. The answer to this puzzling problem could be in self-organized criticality.

Koch¹ has called the attention on the difficulty (maybe impossibility) to store in the genoma all the information required to initialize a network of neurons without the intervention of an external programmer.

Brain function² is largely based on a complex system of connections among its basic components, neurons and synapses. If the sum of excitatory signals (of the order of one millivolt each) that reach a neuron within a short period of time, surpasses some threshold (of approximately tens of millivolts high), the neuron will eventually release an electric signal (spike). After the traumatic event, that the emission of a spike represents, the neurons require a period of time to recover. This period is called the absolute refractory period of the neuron.

By self-organized criticality it is understood the tendency of certain collectively organized systems to reach a steady state without necessity of external tuning of parameters. The lack of a typical size for bursts of activity or avalanches (except the own size of the system) and the lack of a relevant time scale are the main

features of the above mentioned steady state. Self-organized criticality appears in systems and models that, at a first glance, could appear very unlike. It is a quite ubiquitous phenomenon and experimental evidence has been found, among others, in earthquakes³, superconducting vortex avalanches⁴, sand piles⁵ and (maybe?) the brain¹.

Self-organization (some times called self-tuning) has become popular among the scientists that model the brain function⁶⁻¹⁰. It has been used in general problems as, for example, the cortical organization, as well as in the modeling of specific activities as, for instance, the breath regulation. In all these cases the implemented algorithm adapts itself locally to a cost function landscape. In the model to be confronted to experimental results it is not attempted to give a detailed description of the elements of the brain. Instead, each neuron is represented by a barrier that is a relaxed measure of the number of stimulatory inputs that the neuron must receive to fire. When the barrier is high, firing is difficult unless accumulative activity of related neurons lower the barrier enough; the firing would only happen at later times. The barriers are the measure of stability. The modification of a barrier can be thought as either the result of the release of a spike by the own neuron or as the consequence of a received signal that changes the stability of the neuron.

A simple model that represent the main characteristics of all that was explained above, and that can liberate the genoma from the burdensome responsibility of initialize the 10^{14} connections in the brain, is defined by following the simulation sequence: N neurons are distributed on a ring (a line with periodic boundary conditions). A random barrier, B_i , between 0 and 1, is assigned to each neuron. The lowest barrier is detected and the corresponding neuron is fired (this is, at the same time, the updating algorithm and the definition of time step) by assigning a new

random number between 0 and 1 to the barrier and by assigning to its first neighbors new random numbers between 0 and 1. Last, the site that suffers a change in its barrier as a consequence of firing itself is prohibited of firing again during a period of time T_r (the refractory period). Its neighbors are free to fire at any moment if they fulfill the condition of being the lowest. If after a certain time interval T_r a nearest neighbor is fired, the barrier of the temporarily "frozen" neuron is also changed but it continues to be prohibited to produce a spike until a time T_r has elapsed.

After a transient, independently of the initial conditions, the system reaches a stationary state boldly characterized by a step-like distribution for the barrier heights and by a threshold B_c . The spike activity takes place in neurons with barriers below the self-organized critical value B_c . The distribution of the lowest barriers in the critical state vanishes at and above the self-organized threshold.

In the critical state each barrier suffers bursts of activity alternated with long periods of calm. The hanging garden of Babylon shaped picture in Figure 1 presents the instantaneous values of a single barrier, during a time interval, when the system is at the critical state. It seems to present a fractal character: when the time scale is changed the appearance continues to be essentially the same as in the magnification shown.

Now, if at the critical state all the events become correlated in space it is not too difficult to realize that by looking, for a sufficiently long period of time, at the subsequent values of a single barrier, it will be obtained some "comprehension" of what is usually called avalanche. Defining the size s of, what is preferable to call, anti-avalanche (the name will become clear now) as the number of consecutive time steps during which the observed barrier remains constant it is possible to obtain an histogram. In Figure 1 the horizontal segments are the evidence of large anti-

avalanches (the avalanches present in the system during those time intervals are far away from the barrier of interest or are small enough to, even being in the neighborhood of the barrier, not affect it). The vertical punctuated strips are time intervals of "intense" activity, i.e., periods of time during which the barrier is submersed in the sea of an avalanche.

Figure 2 shows the distribution of anti-avalanches in the critical state for a single barrier. The power law reveals the existence of anti-avalanches of all scales. The exponent β in the anti-avalanche distribution $A(s) = s^\beta$ is $\beta = -1.60 \pm 0.04$.

As illustrated by the power law distribution of anti-avalanches, at the critical state, the neurons are connected at all scales. All neurons belonging to a single avalanche should remain in activity at the "same" time period, thus, they might be considered as a single domain of the brain. We thus have a hierarchical organization of neurons up to and including the whole brain and we can speculate that the whole brain acts as a single interconnected neuron; it suffers bursts of activity as a consequence of excitations coming, in some way, from other neurons. A situation similar to this was obtained in the model of Bak and Sneppen¹¹ and was previously suggested by Lovelock¹² for biological evolution. It is, very probably, a general feature of some classes of self-organized critical models and systems.

We have changed the representation of Figure 1 in order to compare it to Figure 2b of Koch (with experimental data provided to him by W. Newsome and K. Britten). In the horizontal axis of Figure 3 we put a tick, with the same height, each time the barrier changes. Both results strongly resemble each other. The similarity between them could be more than simply pictorial. However a rigorous proof of that would require longer measurements of single neurons or in its lack many of the trips shown by Koch. Contrary to what was mentioned by Koch and to what could be

expected, the distribution of spikes in time is not random. Some colleagues at our center were asked, independently, to magnify approximately four times the Figure 2b of Koch and make a low-statistics histogram of the distances between subsequent spikes using a bin size of about one millimeter. All the results gave a one-decade flavor of what should be expected in better quality statistics: a power-law. Figure 4 shows one of the results. The calculated slopes range from -1.79 to -1.53 . The result obtained within the model was -1.6 , a nice result. Corroboration of this result would be an amazing example of self-organized criticality and at the same time will demonstrate the high universality expected in what is believed to be one of the latest evolution products in the nervous system²: the brain. Equally important, the confirmation of this could answer the question on where and how store the information required to initialize the network of neurons: the information is at the same time nowhere and everywhere. The brain self-organizes critically.

Bibliography

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FIGURE CAPTIONS

Figure 1.- Temporal dependence of the value of a barrier when the system is at the self-organized critical state. It has a fractal character: if the time scale is changed the shape continues to be the same, as shown in the zoomed area.

Figure 2.- Distribution of anti-avalanches for a single barrier when the whole system has attained the self-organized critical state. The value of the exponent of the power law is $\beta = -1.60 \pm 0.04$.

Figure 3.- Representation *a la Koch* of the activity of a single model neuron when the whole system has attained the self-organized critical state. Each tick represents a change in the value of the barrier that represents the neuron or, alternatively, the release of a spike.

Figure 4.- Low-statistics histogram of the periods of inactivity or antiavalanches of a single model neuron. The straight line is a guide for the eyes. It has a slope of -1.79.

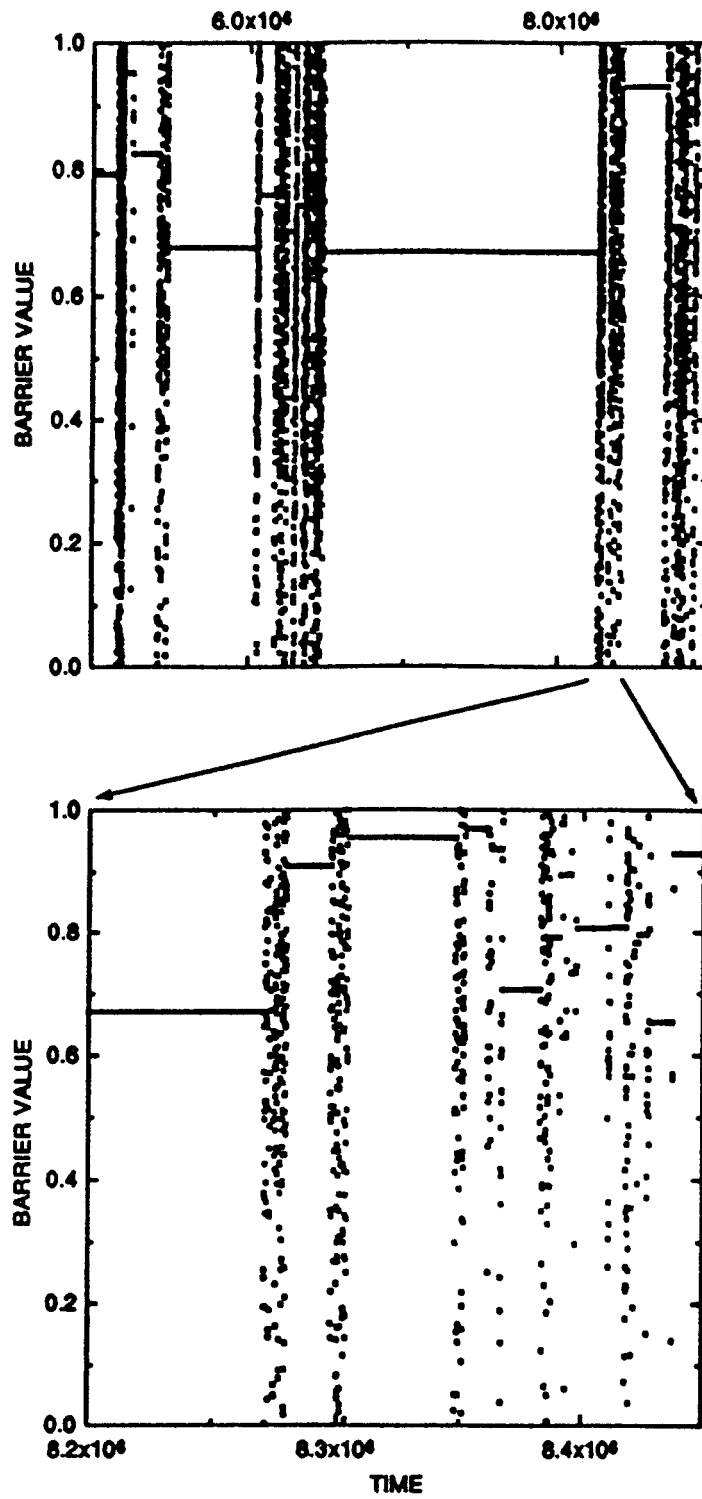


FIGURE 1

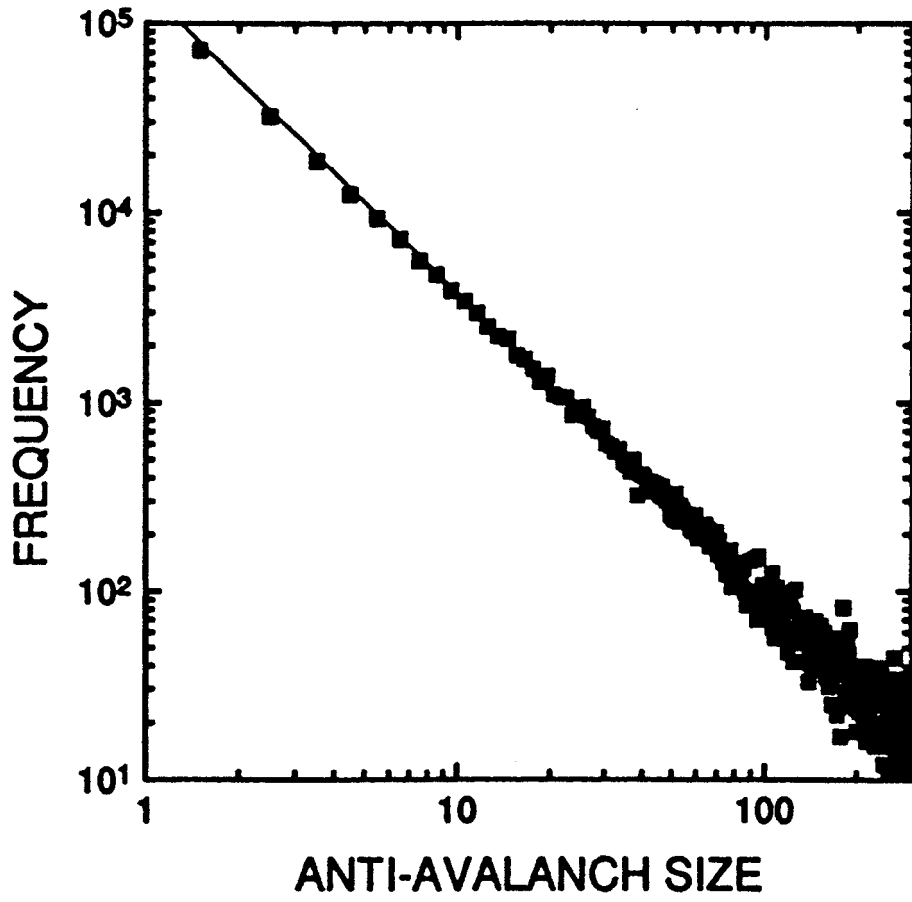


FIGURE 2



FIGURE 3

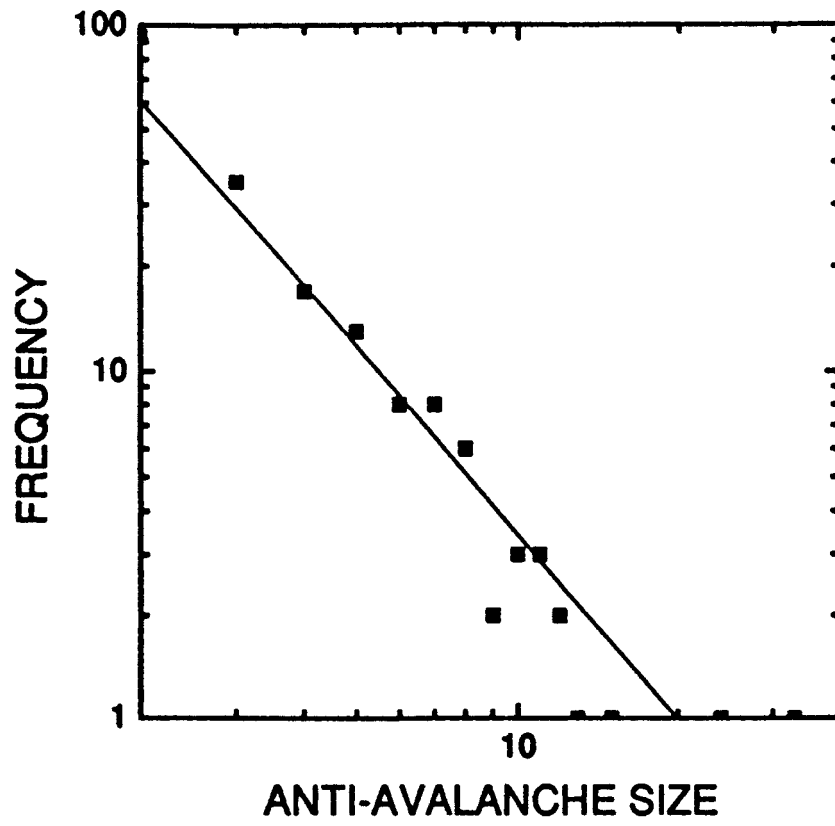


FIGURE 4