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Synaptic plasticity and neuronal refractory time cause scaling behaviour of neuronal avalanches*

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1 Introduction

Neuronal avalanches measured in different cortical systems exhibit a power law behaviour for the size and duration distributions with scaling exponents typical of a mean field **self-organized branching process** [1,2]. These exponents are recovered in neuronal network models implemented on different network topologies, e.g. scale free, random, hierarchical and even regular networks, like the square lattice [3]. This means, the observed exponents are surprisingly robust concerning changes in the underlying structure and **different network topologies lead to the same universality class.** This seems counter-intuitive. The presented results give an explanation by revealing how two neurobiological phenomena, **the refractory period and Hebbian plasticity**, when combined, sculpt the network into a branched structure where few loops are present and avalanche propagation becomes a branching process.

2 Neuronal Model

The model is inspired by **Self-Organised Criticality** (SOC)[4]. Neurons have a potential v_i and are connected by synapses g_{ij}. If a neuron reaches the threshold value it fires to its neighbouring neurons according to:

$$v_j \to v_j + v_i \frac{g_{ij}}{\sum_k g_{ik}}$$

Refractory Period
The firing rate of real neurons is limited by the refractory period. This is implemented by setting a neuron into a refractory state for a certain period. During this time it cannot produce further action potentials.

Activity-dependent Plasticity
Plastic adaptation governs how the network evolves during the avalanche propagations. It follows the principles of **Hebbian plasticity.** Synapses connecting correlated neurons are strengthened according to:

$$g_{ij}(t+1) = g_{ij}(t) + \alpha(v_j(t+1) - v_j(t))/v_c$$

Then all synapses are weakened by the average strength increase:

$$\Delta g(t) = \frac{1}{N_b} \sum_{ij} \delta g_{ij}(t)$$

3 Transition towards a loop-less network

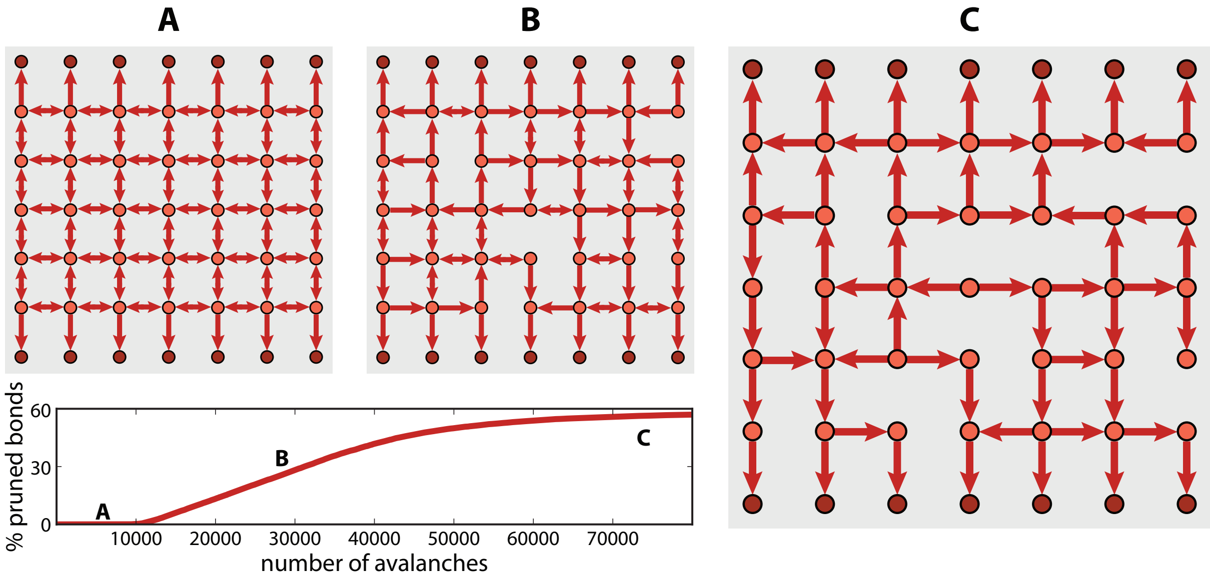

Fig. 1. The initial structure is the square lattice **(A)**. The dark nodes constitute the open boundary at the top and bottom. On the left and right are periodic boundary conditions. An intermediate state of the network is shown **(B)**. The final configuration **(C)** is obtained when plasticity saturates. This final network has no loops, i.e. paths which start and end at the same node.

4 Results

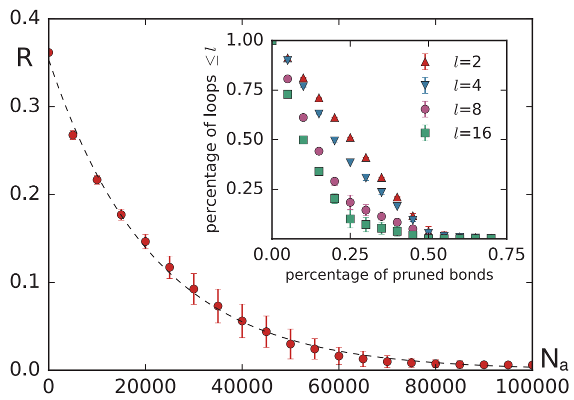

Fig. 2. Backward flow R and number of loops (inset) go to zero.

- Refractory period gives direction to activity propagation
- Backward avalanches are hindered
- Plastic adaptation imprints the shape of avalanches into the structure
- Number of loops decreases as the network becomes branched
- The avalanche propagation becomes a branching process

- Avalanche size distribution follows a power law with an exponential cut-off
- The system exhibits critical scaling
- The scaling exponent is 1.5, the mean field value
- The exponent of similar SOC models on a square lattice is 1.28 [4]
- Refractory period and Hebbian plasticity lead to change in universality class

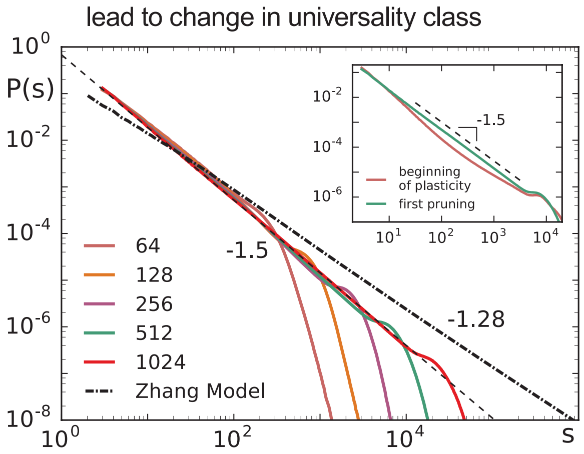

Fig. 3. Avalanche size distribution scales with the system size with the mean field exponent 1.5. The initial network is the square lattice with a side length L={64,128,256,512,1024}

5 Conclusion

Two neurobiological phenomena, the refractory period and Hebbian plasticity, modify the neuronal network into a branched structure. This network transformation is the origin of the mean field exponents in low dimensional regular lattices and explains why these exponents are consistently observed on many different network topologies.

6 References

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