**Modeling Biology**

Interactions between biological neurons are largely based on action potentials (AP) or spikes that are transmitted via synaptic connections with characteristic time courses.

In the leaky-integrate-and-fire (LIF) model the neuron’s soma is modeled as a capacitor which integrates synaptic input and constantly leaks charge. It emits a spike or fires when its voltage crosses the threshold value \( V_{\text{thresh}} \). Whenever a neuron emits a spike the exponentially decaying synaptic conductance \( g_{\text{syn}} \) is increased by the synaptic strength \( w \).

\[
\frac{dE}{dt} = g_{\text{syn}}(t) (E_{\text{th}} - u) + \sum_i g_{\text{syn}}(t) (E_{\text{th}} - u) \\
\frac{du}{dt} = \frac{E_{\text{syn}}}{\tau_{\text{syn}}} + w \sum_i \delta(t - t_{\text{spike}})
\]

After a spike the membrane is clamped to a reset potential \( V_{\text{reset}} \) for a fixed period of time \( \tau_{\text{ref}} \). In the limit \( \tau_{\text{ref}} \to 0 \) the transfer function of the neuron is close to linear. Finite \( \tau_{\text{ref}} \) limit the output. Adding Poisson noise softens the onset of the activation, furthermore this renders the neuron stochastic, enabling an ensemble to sample from a Boltzmann distribution [1].

**Applications and Hardware**

Current small-scale demonstrations on the BrainScaleS platform include pattern recognition and the emulation of generative models of high-dimensional data sets. The latter are based on hierarchical sampling networks, enabled by the neural sampling theory described above. A broad range of hardware-emulated models can be found in [3, 4].

The BrainScaleS machine room consists of 20 wafer systems with up to 4 million configurable neurons and up to one billion synaptic connections. It runs with a constant speedup of 10,000 compared to biological real time.

**References**

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**Relation to Spin Glasses**

Boltzmann machines are mathematically equivalent to spin glasses. In networks of LIF neurons we can therefore observe known physical phenomena such as the Curie law and hysteresis.

To translate between different interaction shapes we match the mean interaction strength within the refractory time (shaded area).

\[
W = 4J \\
b = 2h - 2W \\
h = \frac{1}{2} b + W
\]

The BM system, unlike the spin system, is not symmetric around zero, meaning the point \( h = 0 \) requires fine tuning of the parameters. This makes most of the physical effects much harder to measure.

**New Physics?**

We parameterize the 2D Ising model as \( W, b \), with \( b = -2Wb \), and scan the two parameters to simulate a changing temperature and external field. Glauber dynamics (left) show increasing susceptibility for \( T \to T_c \) and a hard boundary at \( h = 0 \), \( b = 1 \), independent of the spatial pattern of the initialization (with \( A = 0.5 \)). For spiking neurons, the ensemble behavior can be fundamentally different.

At low temperature, we observe an unusually strong dependence of the ensemble behavior on the initial topology. More importantly however, depending on the interaction shape, we observe a large diversity of the resulting state diagrams. Taking into account the additive nature of PSPs from the same presynaptic neuron further complicates the picture.

These differences are so far without firm theoretical understanding, but they might turn out to be essential to understanding cortical computation, which is often hypothesized to occur at the edge of criticality.