



*Computational Neuroscience Group
Department of Physiology
University of Bern*

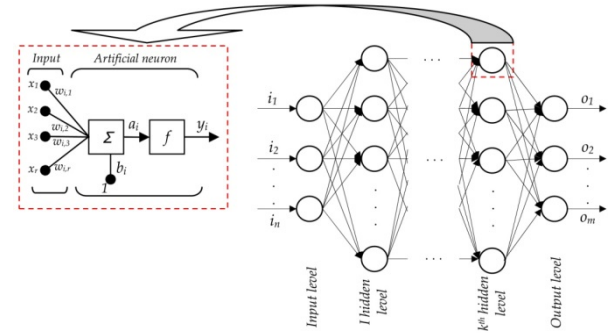
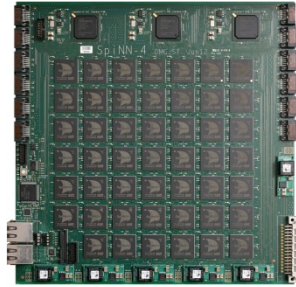
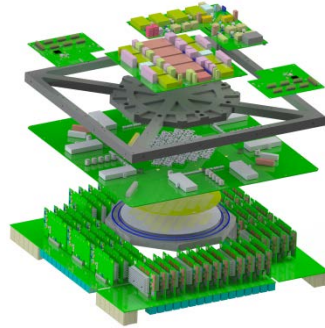
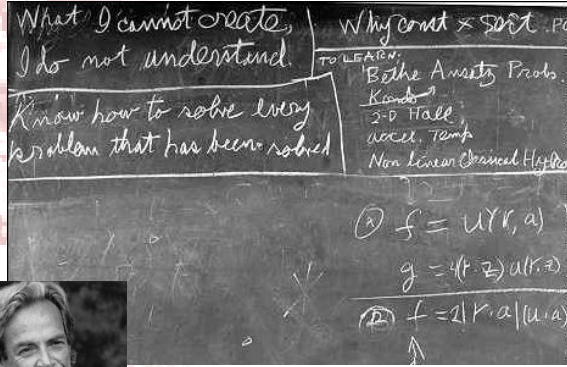
Computing with physics

From biological to artificial intelligence
and back again

Mihai A. Petrovici

*Electronic Vision(s)
Kirchhoff Institute for Physics
University of Heidelberg*

Bio-inspired artificial intelligence



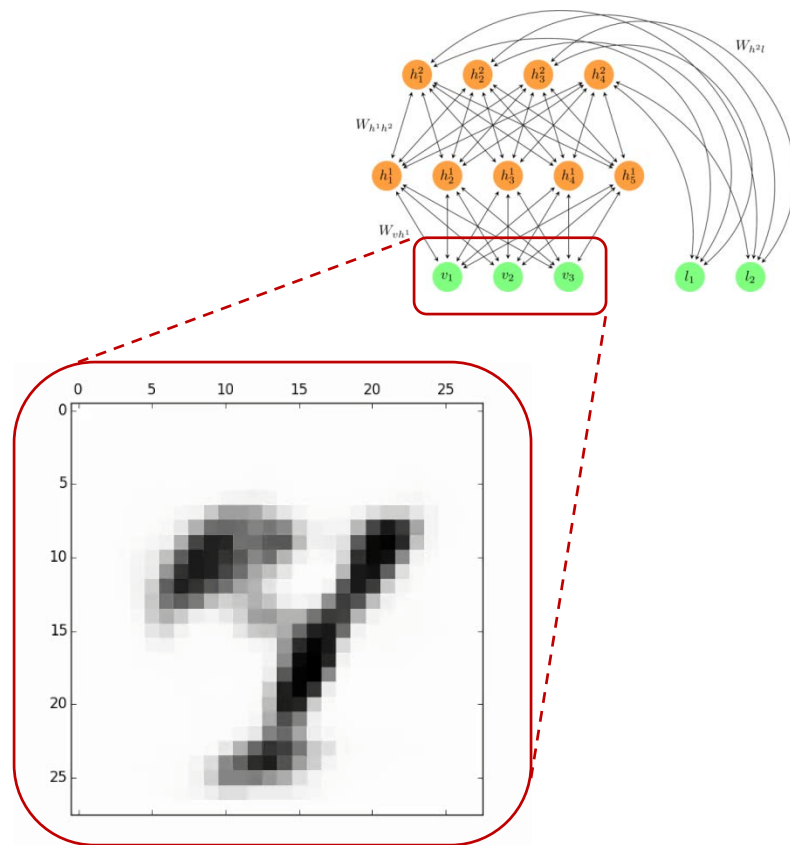
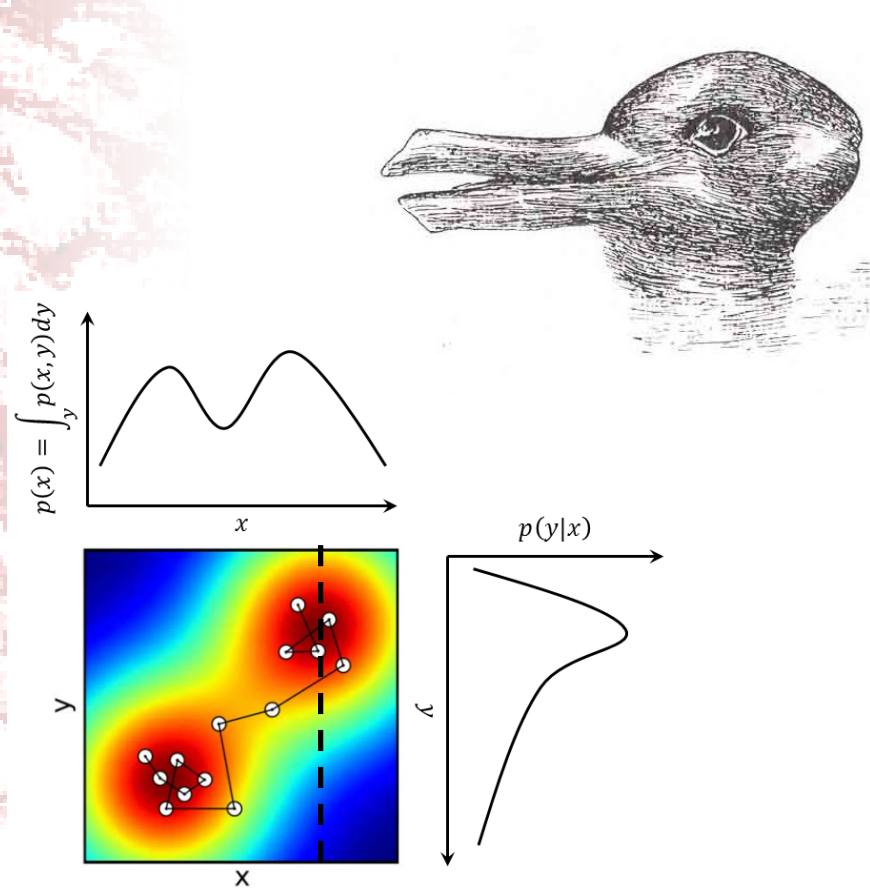
clean & easy, but not as efficient

messy & hard, but powerful

Why spikes?

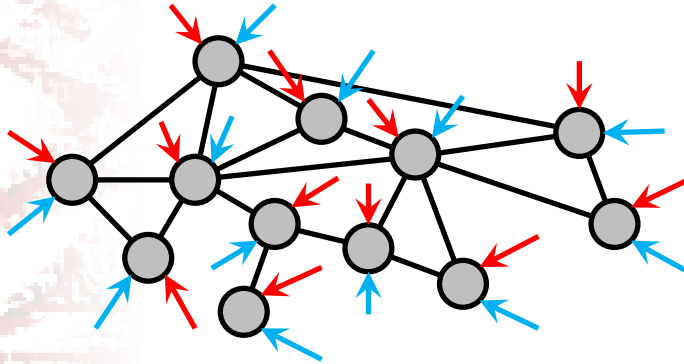


Sampling-based Bayesian computation

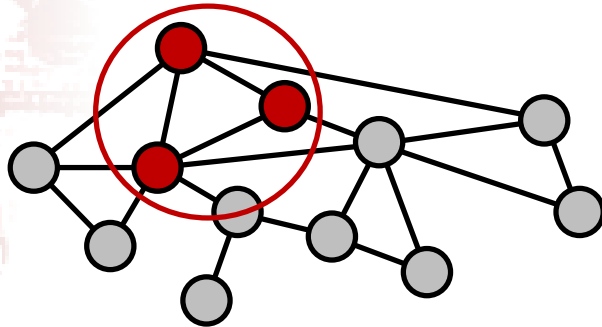


Whence stochasticity?

Injection of stochasticity



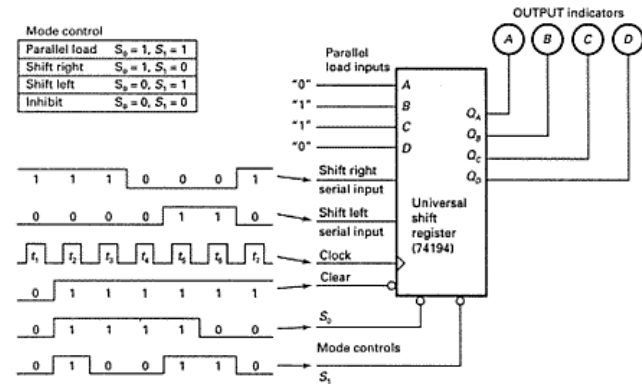
Embedded stochasticity



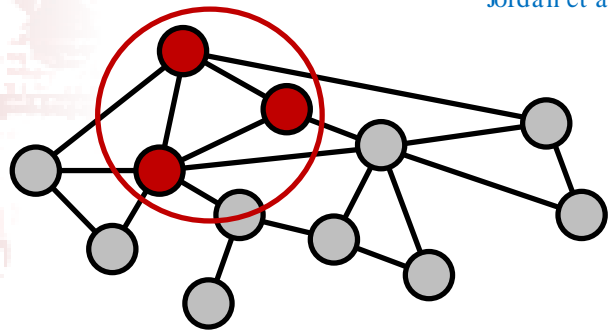
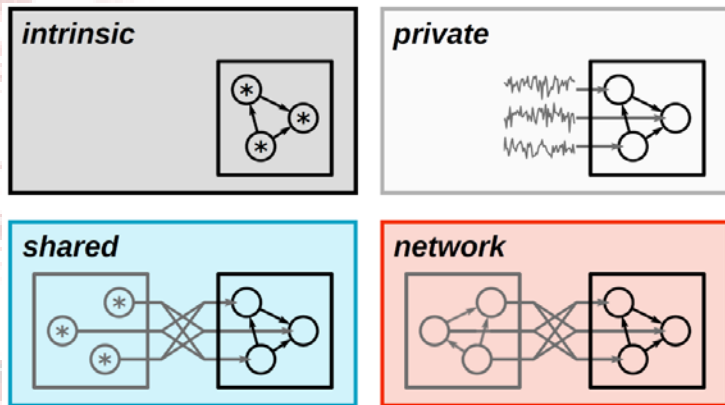
Stochasticity in continuous systems



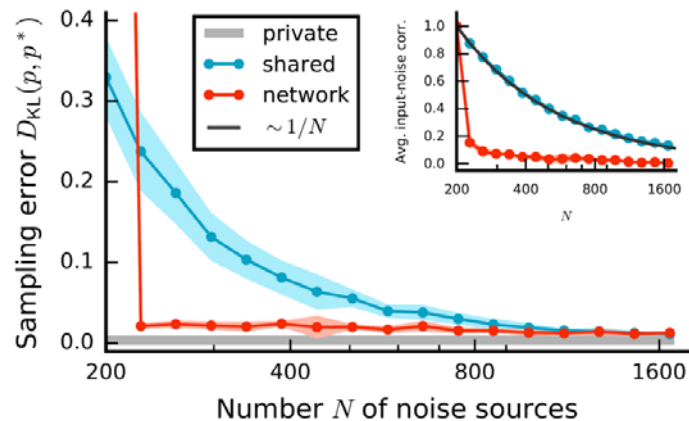
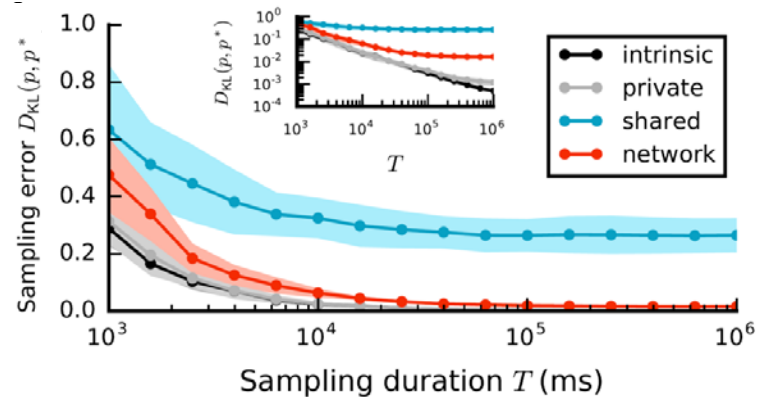
Stochasticity in (dedicated) discrete systems



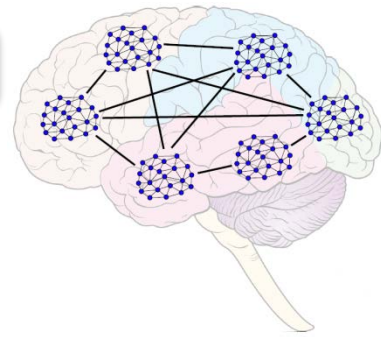
(Pseudo)randomness in deterministic spiking networks



Jordan et al. (2017)



Stochasticity from function: Bayesian inference & dreaming

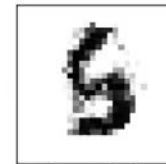
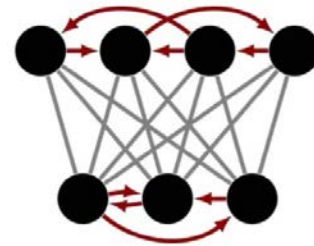
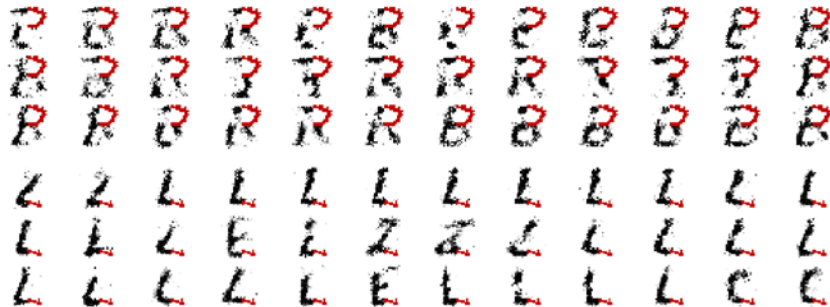
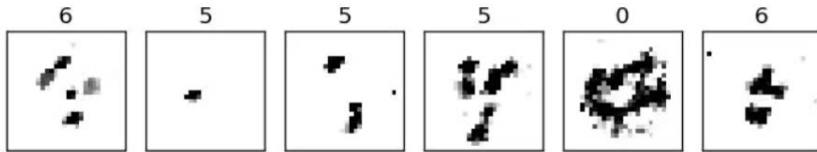


hidden neurons

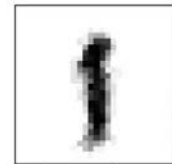


time: 50.00 ms

visible neurons

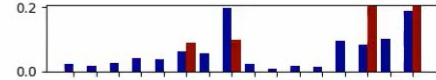
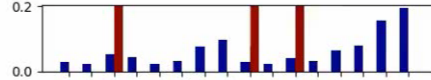
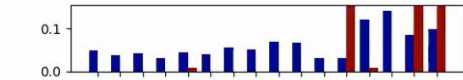
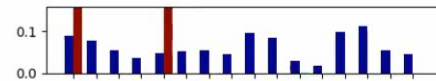
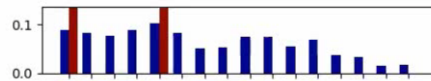
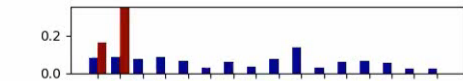
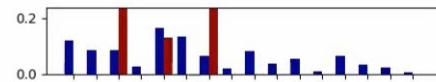
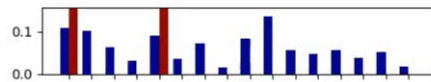
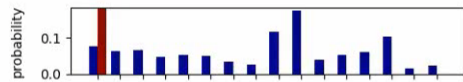
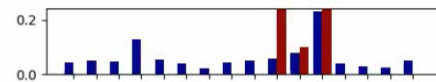
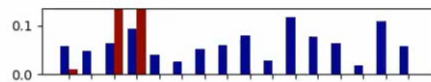
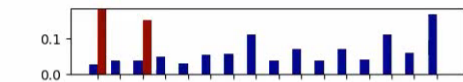
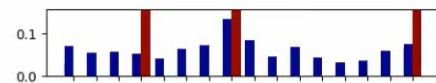
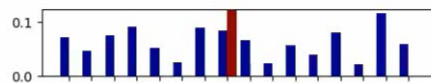
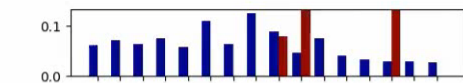
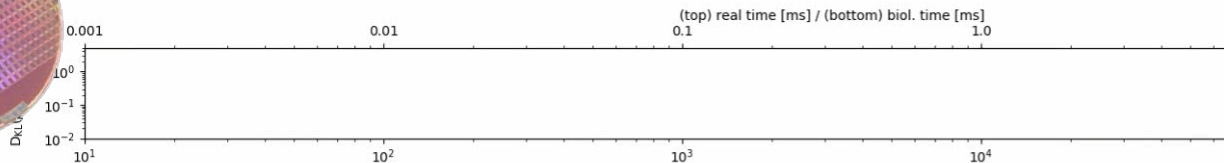
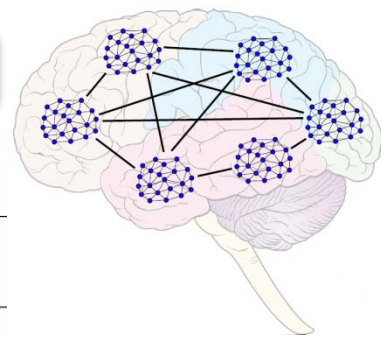
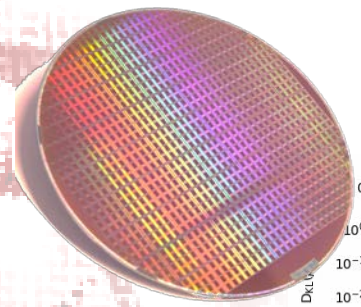


after training
50ms



Poisson reference

Physical stochastic computation without noise



Superior mixing in spiking networks

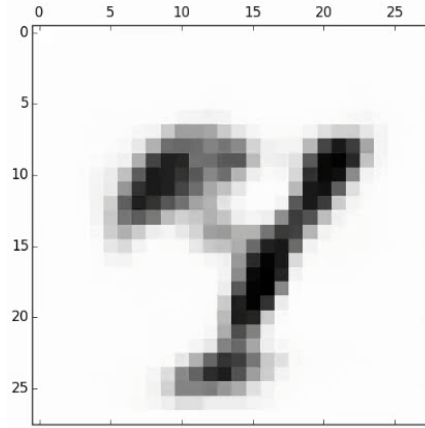
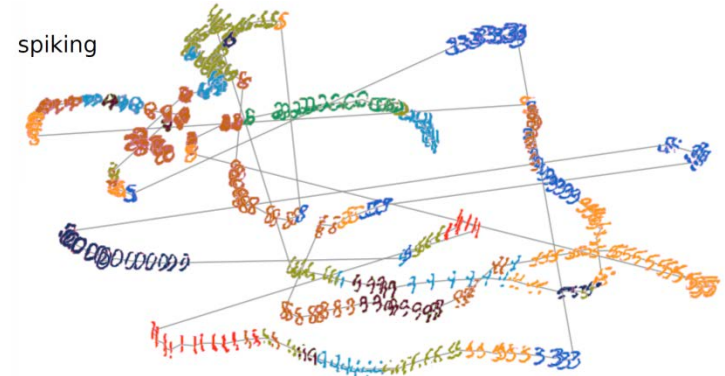
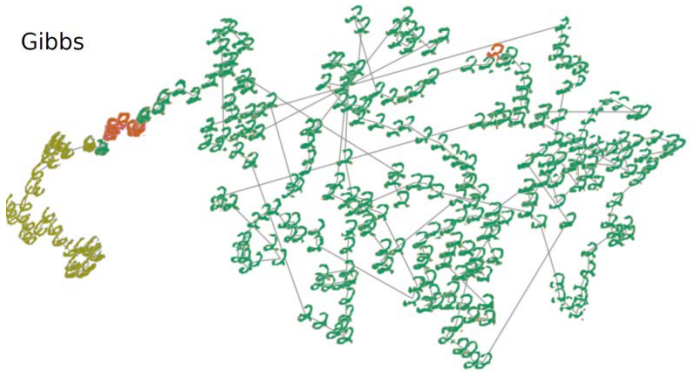
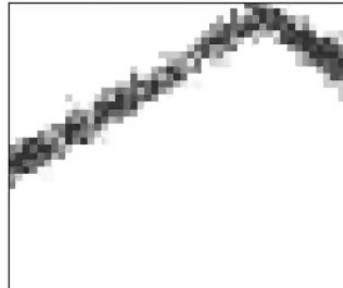


Image 0: 1/980 samples
 $\tau_{rec} = 10$ ms, $U = 1$

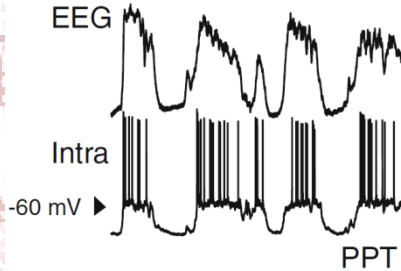


$\tau_{rec} = 50$ ms, $U = 0.22$

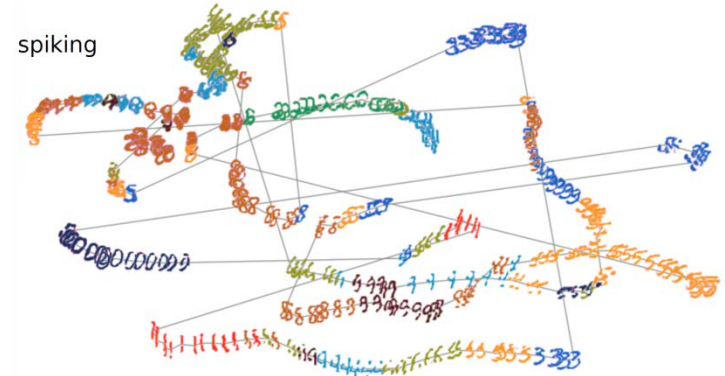
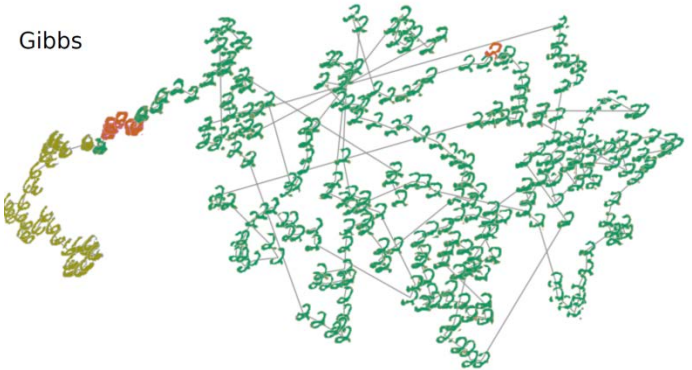
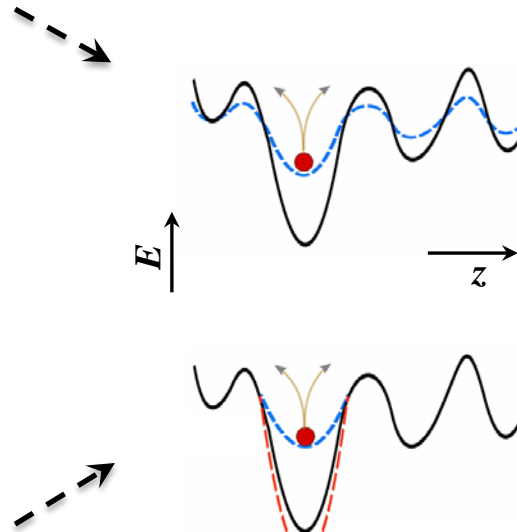
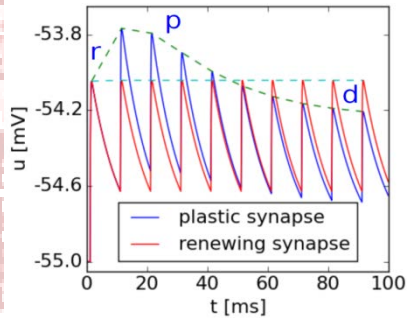


Biological mechanisms for superior mixing

cortical oscillations



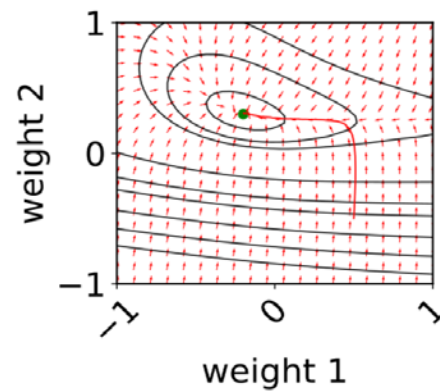
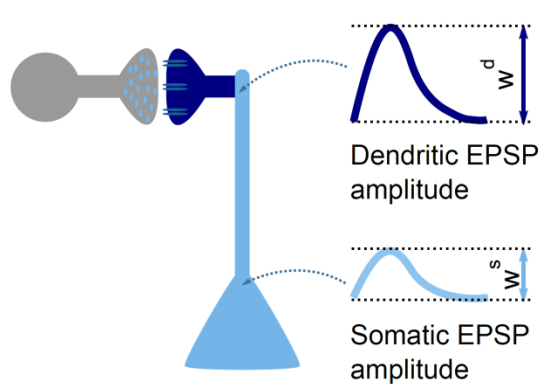
short-term synaptic plasticity



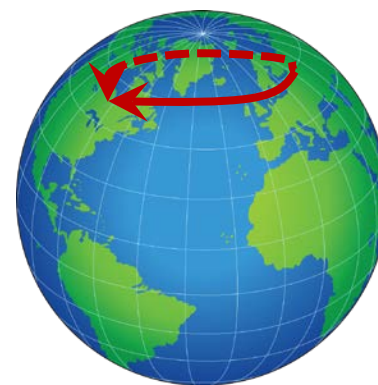
Which way is down?



What's wrong with Euclidean gradient descent?

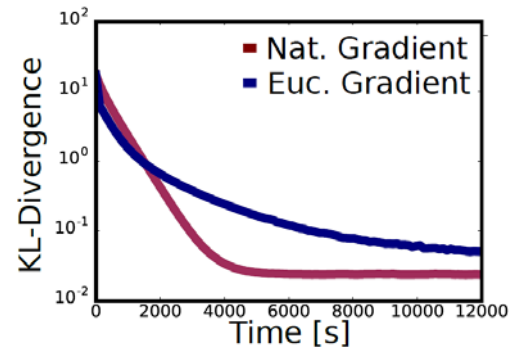
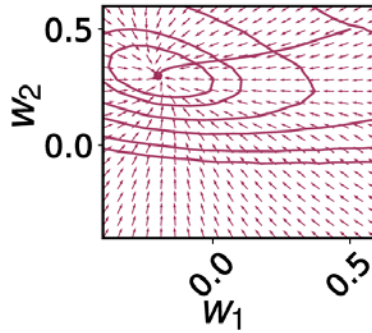
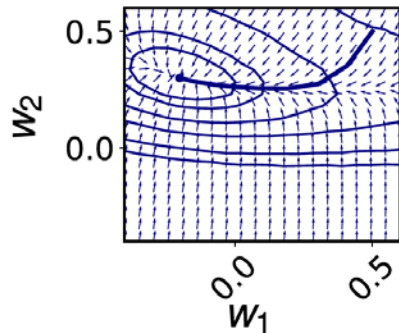
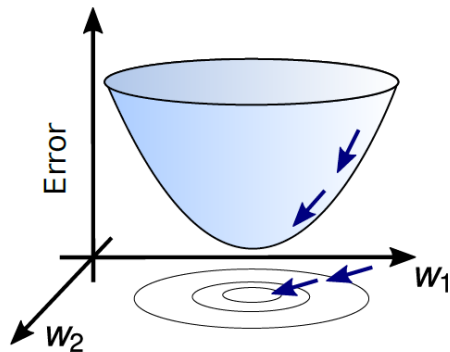


$$\Delta w^{\text{syn}} = -\eta \frac{\partial C(\alpha w^{\text{syn}})}{\partial w^{\text{syn}}} = -\eta \alpha \frac{\partial C(w^{\text{syn}})}{\partial w^{\text{syn}}}$$



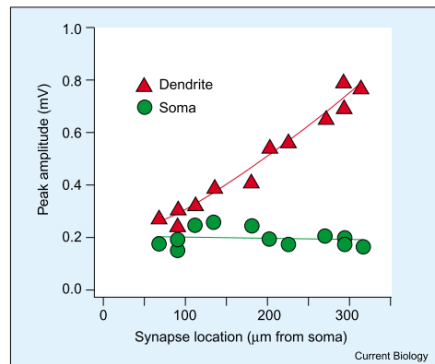
$$\nabla^n = G(w)^{-1} \nabla^e$$

Synaptic plasticity as natural gradient descent

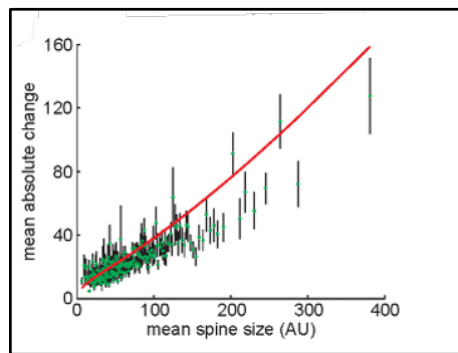


local learning:
$$\Delta^n \mathbf{w} = \eta \int_0^T \gamma_0 \left[y^* - \phi(V) \right] \frac{\phi'(V)}{\phi(V)} \left(\frac{x^\epsilon}{r} - \gamma_1 + \gamma_2 \mathbf{w} \right) dt$$

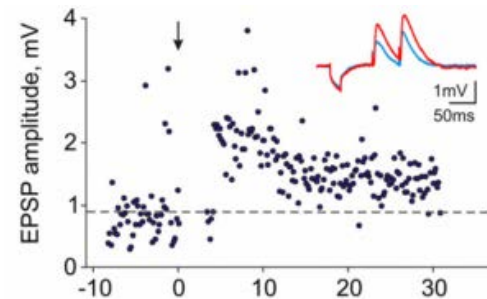
Kreutzer et al., in prep.



Häusser et al. (2001)

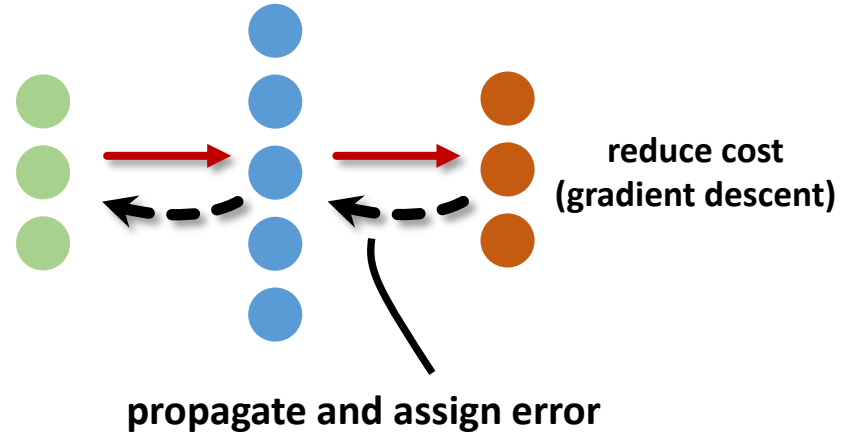
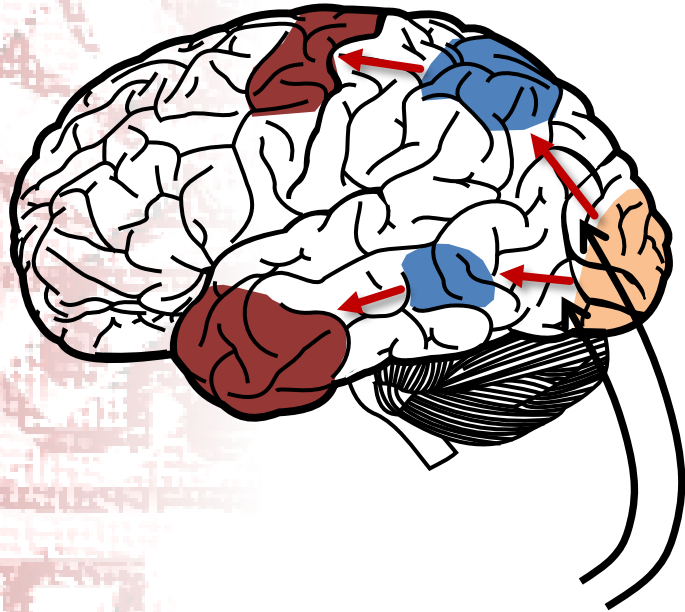


Loewenstein et al. (2011)



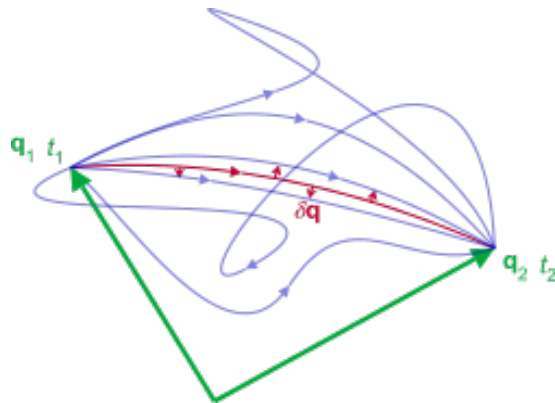
Chen et al. (2013)

Hierarchical networks and the credit-assignment problem



La grangian mechanics

principle of (least) stationary action



$$\delta \left(\int dt L(\mathbf{q}, \dot{\mathbf{q}}) \right) = 0$$

\Downarrow

$$\frac{\partial L}{\partial q_i} - \frac{d}{dt} \frac{\partial L}{\partial \dot{q}_i} = 0$$

fundamental principle in

- mechanics
- geometrical optics
- electrodynamics
- quantum mechanics
- ...
- **neurobiology?**

Euler-La grange equations of motion

Lagrangian mechanics for neuronal networks

$$E(\mathbf{u}) = \sum_i \frac{1}{2} \|\mathbf{u}_i - \mathbf{W}_i \bar{\mathbf{r}}_{i-1}\|^2 + \beta \frac{1}{2} \|\mathbf{u}_N - \mathbf{u}_N^{\text{tgt}}\|^2 \xrightarrow{\mathbf{u} = \tilde{\mathbf{u}} - \tau \dot{\tilde{\mathbf{u}}}} L(\tilde{\mathbf{u}}, \dot{\tilde{\mathbf{u}}})$$

$$\frac{\partial L}{\partial \tilde{\mathbf{u}}_i} - \frac{d}{dt} \frac{\partial L}{\partial \dot{\tilde{\mathbf{u}}}_i} = 0$$

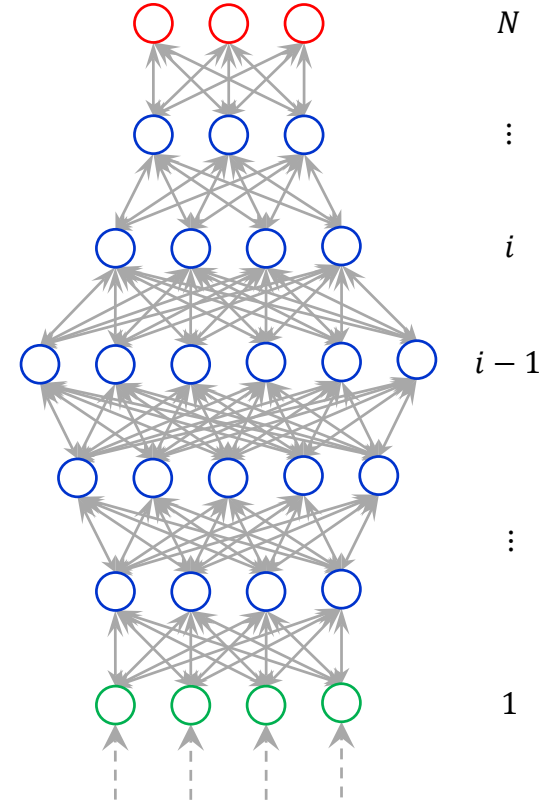
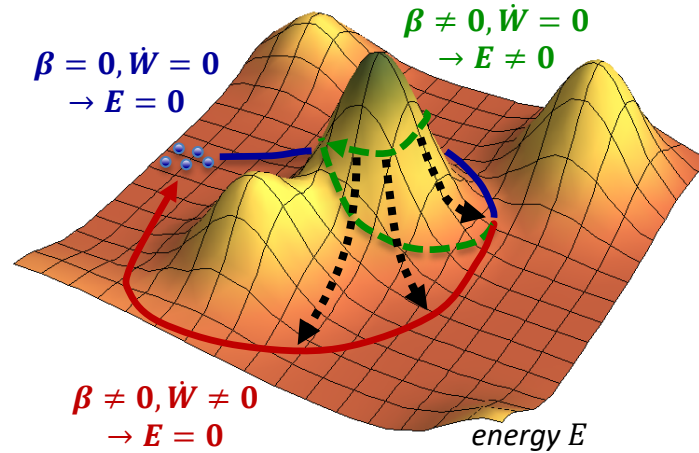
$$\dot{\mathbf{W}}_i = -\eta \frac{\partial E}{\partial \mathbf{W}_i}$$



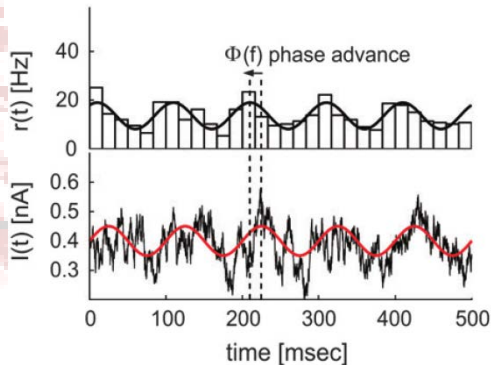
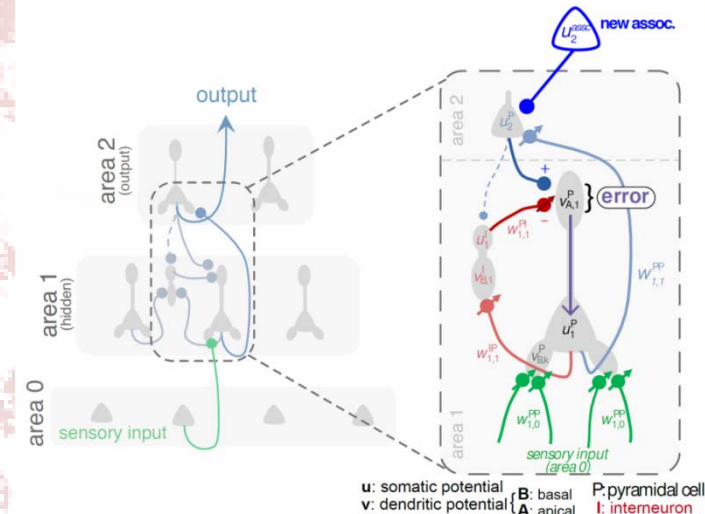
$$\tau \dot{\mathbf{u}}_i = \mathbf{W}_i \bar{\mathbf{r}}_{i-1} - \mathbf{u}_i + \mathbf{e}_i \rightarrow \text{neuron dynamics!}$$

$$\bar{\mathbf{e}}_i = \bar{\mathbf{r}}'_i \odot [\mathbf{W}_{i+1}^T (\mathbf{u}_{i+1} - \mathbf{W}_{i+1} \bar{\mathbf{r}}_i)] \rightarrow \text{error backprop!}$$

$$\dot{\mathbf{W}}_i = \eta (\mathbf{u}_i - \mathbf{W}_i \bar{\mathbf{r}}_{i-1}) \bar{\mathbf{r}}_{i-1}^T \rightarrow \text{Urbanczik-Senn learning rule!}$$

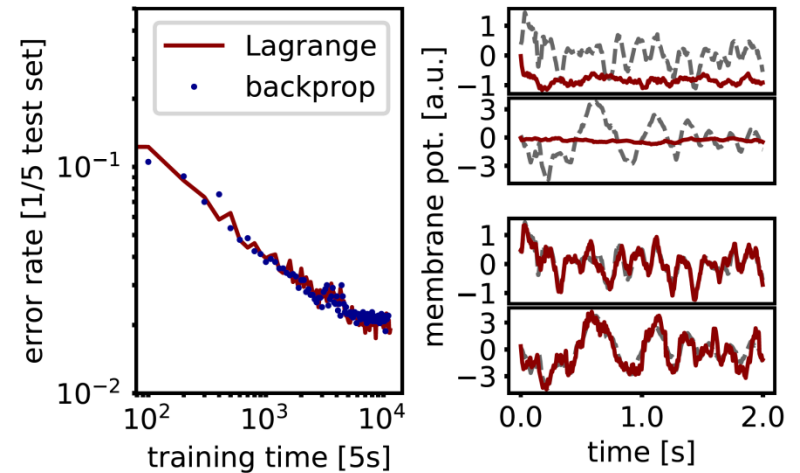


Biophysical implementation

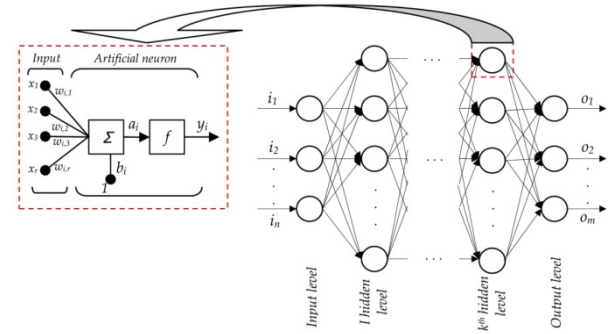
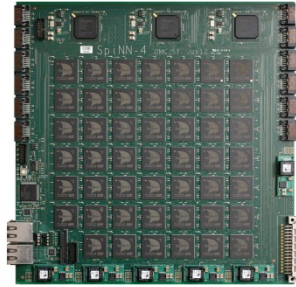
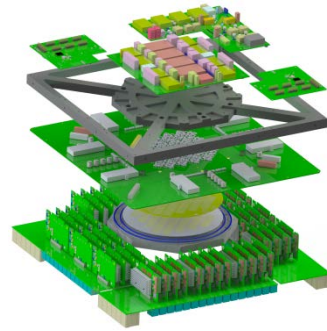


$$r(t) \approx \varphi(u(t + \tau))$$

- local representation of errors for plausible synaptic plasticity
- prospective coding for continuous dynamics



Bio-inspired artificial intelligence



messy & hard, but powerful

clean & easy, but not as efficient

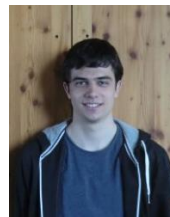
Some of the neural networks behind our neural networks



Dominik Dold



Akos Kungl



Andi Baumbach



Agnes Korcsák-Gorzo



Luzziwei Leng



Elena Kreutzer



Oliver Breitwieser



Jakob Jordan



Joao Sacramento



Walter Senn



Johannes Schemmel



Karlheinz Meier