1. Bayesian learning in spiking neural network models

*General theme*: The theoretical framework of Bayesian statistics is commonly considered as an intuitively attractive model for representing and processing uncertain information in the brain. It has received a lot of attention in computational studies of learning and inference mechanisms underlying brain function. Since the Bayesian machinery for capturing probabilistic information in distributed neural networks corresponds to a commonly accepted and biologically inspired Hebbian idea of synaptic processes taking place in the connections between cells, there have been numerous attempts to adapt Bayesian inference as an unsupervised learning principle. In this context it is particularly challenging to translate Bayesian algorithms from abstract theoretical formulations to biologically plausible computations in spiking neural network models. In the following projects a student will support the ongoing research efforts in the lab, where our own Bayesian learning scheme (Bayesian Confidence Propagating Neural Network, commonly referred to as BCPNN) has been developed.

*Project ideas*

a) Benchmarking synaptic Bayesian-Hebbian learning rules in a spiking sparse activity cortical associative memory  
b) Benchmarking synaptic Bayesian-Hebbian learning rules in popular pattern recognition/machine learning tasks.  
c) Simulation and analysis of spiking neural network models pre-trained with a Bayesian-Hebbian learning algorithm; studying the implication of Bayesian learning on the network dynamics and function.

2. Simulations and analysis of spiking attractor memory network models

*General theme*: An attractor theory of brain computations has received considerable attention in computational neuroscience. The functionality of attractor networks has been found helpful in explaining various perceptual and memory phenomena. Also, some features of the dynamics exhibited by these models have been shown to be in agreement with biological data. In our lab we have a long tradition of simulating attractor memory networks to model the cortical computations. As a result, we have developed a modular architecture corresponding to the neural circuitry in the superficial cortical layers. Our recent focus has been on studying their dynamical and functional properties in the context of experimental findings on relevant cortical phenomena. The proposed projects are part of ongoing research into more fundamental characteristics of our models providing insights into key mechanisms underlying their robustness.

*Project ideas*

a) Studying the effect of different connectivity patterns, network architectures and their dimensionality on the dynamics and function of the attractor model.  
b) Investigating the sensitivity of the model to the level of biological detail being accounted for (discussion on the required level of complexity and the relevance of biological constraints).
c) Exploring population-level (e.g. simple mean-field approximation) approaches to describing the neural dynamics exhibited by our modular attractor network.

d) Exploring synaptic working memory in a spiking modular attractor network. Demonstrating how fast Hebbian or non-Hebbian synaptic plasticity can form attractors by one-shot learning, and how these memories can be replayed spontaneously as well as how they can be triggered by stimuli.

3. Visualisation in large-scale neural modelling

General theme: Visualisation is one of the most neglected aspect of a rapidly developing field of computational biology. Only recently can we observe an emerging trend for combining neural simulation frameworks with visualisation software. Still there are a plethora of challenging problems that need to be urgently addressed (high-dimensional data, pre-processing, integration with a simulation software, 3-D visualization of ongoing brain model activity, demands for purely visual aspects, interactive environment) to render visualisation a practical tool in computational studies. This is envisaged to facilitate computational modelling and assist in demonstrating scientific findings.

Project ideas

a) Visualisation of existing data produced by models (different types of high-dimensional spatiotemporal data are available).

b) Conceptual integration with simulating environment to help with data pre-processing (or post-processing) and facilitate interactive mode with the user.

c) Review of the state-of-the-art methodology and a motivated choice of a tool for the computational problem at hand.

4. Development and testing of brain-inspired network architectures for generic processing of big data

General theme: Brain-inspired computing has long been considered as a particularly appealing concept in a broad field of information science. Its good reputation is largely due to the impressive capabilities of information processing in the brain, which robustly handles large volumes of noisy multi-modal data received in continuous streams. With the increasing availability of powerful computing platforms and intensive development of brain models as well as a growing body of knowledge about computational mechanisms underlying brain function, there is a surge of interest in adapting these functional aspects to devise algorithms for more generic data processing. These efforts are urgently needed and particularly relevant to real-world problems involving so-called big data, for example in exploratory analysis of large volumes of high-dimensional neuroimaging data for research or clinical purposes.

Project ideas

a) Adapting the existing brain-inspired methodology (developed in the lab and deployed on the KTH’s supercomputers at PDC) to neuroimaging data mining.
b) Novel contributions to our cortex-inspired approach to the extraction of spatio-temporal features from neuroimaging or speech data.

c) Testing robustness (sensitivity analysis, noise handling capabilities, computational speed) and benchmarking of brain-inspired data analysis methodology developed in the lab using various pattern recognition/machine learning problems.

5. Investigations into parallel implementations and simulations of brain network models on graphics processing unit (GPU) clusters

*General theme*: Simulations of large-scale brain models have gained growing importance in neuroscience mostly due to the better availability of comprehensive sets of relevant experimental data and, certainly, due to continuously increasing computational power. In the broad field of scientific computing the latter factor is particularly appreciated as it allows researchers to expand the complexity and size of their models. The majority of brain models are nowadays deployed on supercomputers. However, their availability is rather limited and they are commonly dedicated to large-scale simulations. Recently, graphics processing units (GPUs) have attracted attention as cheaper and more widely accessible simulation platforms, particularly for prototyping and evaluating models at lower-scales. Developments of GPU environments for neural simulations are still at early stages, especially when compared to supercomputer platforms. This opens up a lot of interesting research opportunities and the proposed projects within this theme could serve as suitable starting points.

*Project ideas*

a) Testing of existing GPU software for neural simulation. Potential development and a comparative analysis of parallel implementations of simple neural models (spiking or more abstract neural networks).

b) Investigations into parallel simulations of simple brain models (distributed spiking or rate-based models, basic mean-field models etc.) at different scales deployed on GPU clusters using different programming interfaces - OPEN CL and CUDA.

6. Inference about simulated neural systems from the generated data

*General theme*: The proliferation of neural modelling studies along with rapidly expanding dimensions of microscopic and mesoscopic recordings of neuronal activities in the brain have not been matched yet with effective algorithms for their processing. It is particularly insightful to study so-called spiking activity and/or field potentials produced by populations of cells as they provide direct evidence about functional and structural aspects of the information about the underlying neural circuits. The problem amounts to parallel processing of high-dimensional nonstationary point and/or continuous stochastic processes and designing a model for inference about various characteristics of the underlying neural source (system) of interest. The methods investigated in the project will be evaluated on the existing data sets generated in neural simulations.

*Project ideas*
a) A massively parallel search for spatio-temporal patterns, identification of complex synchronous effects and their validation, clustering and quantifying the distance between spike trains etc.

b) Studies of neural synchrony and correlations, development of new methods and/or comparative analysis of the state-of-the-art techniques.

c) Devising a tool for analysis of spike or field potential data (generated by models but applicable to actual electrophysiological recordings from the brain tissue) and visualisation of the results.

7. Relaxation labelling applied to robot visual processing.

One useful approach to real-time segmentation in the visual domain employed by the CVAP group is so called relaxation labelling. This amounts to representing different possible local features of local image content (labels), setting up compatibility coefficients between these labels. The resulting network is then iterated when an input image is presented, and the output gives hypotheses for groping of nearby pixels, i.e. segmentation. This algorithmic structure is almost isomorphic to a one-layer modular cortical network model, developed in our lab. Possible project together with Mårten Björkman, CVAP.