Models for Neural Spike Computation and Cognition

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This monograph addresses the intertwined mathematical, neurological, and cognitive mysteries of the brain. It first evaluates the mathematical performance limits of simple spiking neuron models that both learn and later recognize complex spike excitation patterns in less than one second without using training signals unique to each pattern. Simulations validate these models, while theoretical expressions validate their simpler performance parameters. These single-neuron models are then qualitatively related to the training and performance of multi-layer neural networks that may have significant feedback. The advantages of feedback are then qualitatively explained and related to a model for cognition. This model is then compared to observed mild hallucinations that arguably include accelerated time-reversed video memories. The learning mechanism for these binary threshold-firing "cognon" neurons is spike-timing-dependent plasticity (STDP) that depends only on whether the spike excitation pattern presented to a given single "learning-ready" neuron within a period of milliseconds causes that neuron to fire or "spike". The "false-alarm" probability that a trained neuron will fire for a random unlearned pattern can be made almost arbitrarily low by reducing the number of patterns learned by each neuron. Models that use and that do not use spike timing within patterns are evaluated. A Shannon mutual information metric (recoverable bits/neuron) is derived for binary neuron models that are characterized only by their probability of learning a random input excitation pattern presented to that neuron during learning readiness, and by their false-alarm probability for random unlearned patterns. Based on simulations, the upper bounds to recoverable information are ~0.1 bits per neuron for optimized neuron parameters and training. This information metric assumes that: 1) each neural spike indicates only that the responsible neuron input excitation pattern (a pattern lasts less than the time between consecutive patterns, say 30 milliseconds) had probably been seen earlier while that neuron was "learning ready", and 2) information is stored in the binary synapse strengths. This focus on recallable learned information differs from most prior metrics such as pattern classification performance and metrics relying on pattern-specific training signals other than the normal input spikes. This metric also shows that neuron models can recall useful Shannon information only if their probability of firing randomly is lowered between learning and recall. Also discussed are: 1) how rich feedback might permit improved noise immunity, learning and recognition of pattern sequences, compression of data, associative or content-addressable memory, and development of communications links through white matter, 2) extensions of cognon models that use spike timing, dendrite compartments, and new learning mechanisms in addition to spike timing- dependent plasticity (STDP), 3) simulations that show how simple optimized neuron models can have optimum numbers of binary synapses in the range between 200 and 10,000, depending on neural parameters, and 4) simulation results for parameters like the average bits/spike, bits/neuron/second, maximum number of learnable patterns, optimum ratios between the strengths of weak and strong synapses, and probabilities of false alarms.

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