Hardware computation of conductance-based neuron models

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Keywords: silicon neurons, conductance-based models, simulation tool, plasticity rules.

Abstract:

We review different applications of silicon conductance-based neuron models implemented on analog circuits. At the single-cell level, we describe a circuit in which conductances are programmed to simulate various Hodgkin-Huxley type models; integrated in a hardware/software system, they provide a simulation tool; an illustrative example is the simulation of bursting neurons of the thalamus. At the network level, we present a mixed analog-digital architecture, where the connectivity and the plasticity rules are implemented digitally and are therefore very flexible. These circuits provide valuable tools for real-time simulations, including hybrid applications where single-neuron or network models are interfaced with biological cells.

Introduction:

Understanding how neurons and networks can process information through their electrical activity is one of the major issues of computational neuroscience. Theoretical approaches have made successful use of neural simulation software packages dedicated to biologically realistic simulations. However, there are still difficult compromises to be done between the precision of the models and the computing speed that limits the model's complexity, at the single neuron level as well as at the network level. We propose an alternative technical approach for temporal simulation, based on hardware real-time computation of conductance-based neuron models. We will present in this paper the basics principles for the hardware integration of such models, and illustrate some applications and experimental results. We end up by proposing a new structure for mixed analog/digital simulation systems based on analog artificial neurons.

Methods:

To implement Hodgkin-Huxley type models on analog circuits, we designed specific analog integrated circuits (ASICs) which exploit the intrinsic voltage-current of individual transistors (bipolar and MOSFET) to simulate the membrane equation of neurons including voltage-dependent (or even calcium-dependence) conductances [1]. Synaptic connections can also be modeled using a similar representation, or using a kinetic model. The models variables (state variables, conductances, ionic currents, membrane voltage) are identified to electrical variables in the circuit (currents, voltages). Each ionic conductance, source of an associated ionic current, and described by a set of non-linear equations (Hodgkin-Huxley formalism), is computed by a specific circuitry of transistors, resistors, and capacitors. A

current-mode translinear design approach has been chosen, to optimize the circuit design and minimize the silicon area. Conductance sub-circuits are organized as shown in figure 1-A, to sum the ionic currents on a membrane capacitance. As the integrated circuit dynamics strictly replicate the model's ones, and due to the analog mode of computation, the circuit processes the model's variables continuously and in real-time.

To exploit at best those analog silicon neurons, we built complete simulation systems. They rely on an analog processing core, but can be used just like classical simulation tools for computational neurosciences. This implies that the model's parameters are tunable, and that a single ASIC is able to process a whole range of conductances models. Via dedicated circuit inputs, up to 8 parameters are handled for each ionic conductance, as well as for synaptic connexions (see figure 1-B).

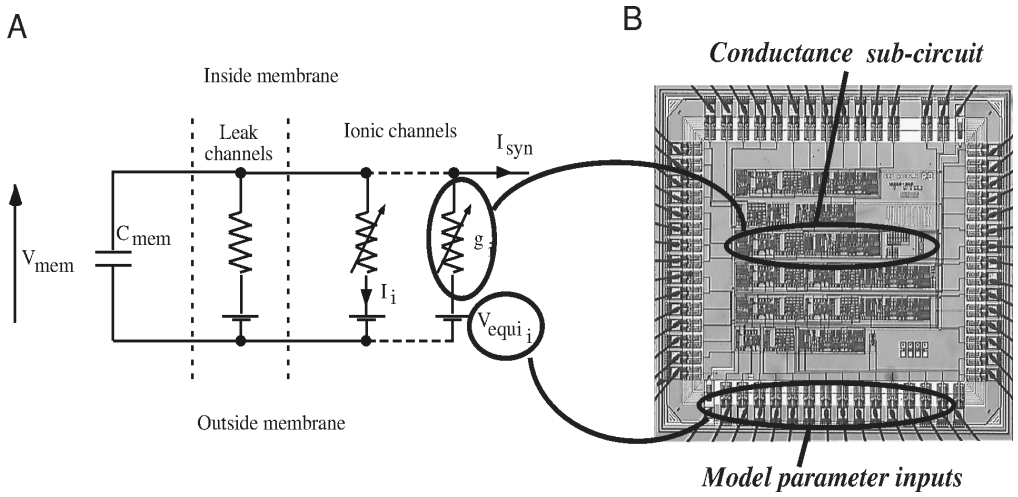

Figure 1: A: Electrical equivalent circuit of excitable membrane, following Hodgkin-Huxkey formalism – **B:** Microphotograph of an analog conductance-based ASIC (technology: AMS BiCMOS 0.8 microns, chip area: 4x4mm^2), input pads receive voltages to set the model parameters; one silicon row corresponds to one conductance sub-circuit.

Electronics boards support these circuits, and are connected to a standard computer. The computer runs a user interface, to control the hardware models and process the simulation results. Direct analog outputs of the chips are available for external connections. They replicate the neuron membrane voltages and the synaptic currents; they also allow the construction of hybrid neural networks, in which hardware artificial neurons are connected to living neurons, via artificial synapses and intracellular micro-electrodes (see next paragraph). A custom software has been developed to drive the hardware; it also provides a user interface to set the neurons structure (number of conductances), the conductance models parameters, and to control the simulation. The system also allows the simulation of small neural networks, provided that the global number of conductances does not overflow the circuits capacity.

The structure of a simulation system we developed, 'Vortex', is described in figure 2. Experimental results of the following paragraphs have been obtained using the 'Vortex'.

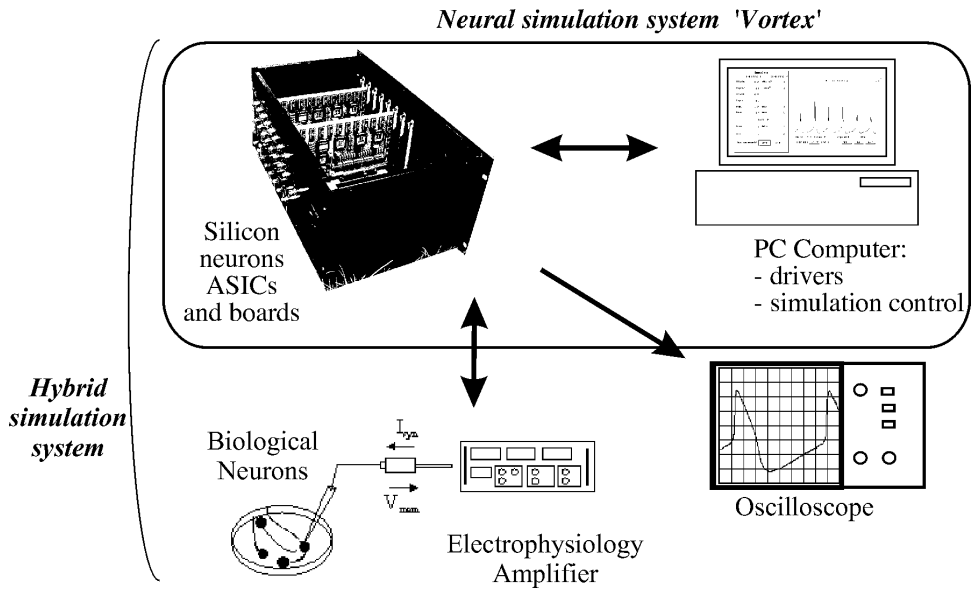

Figure 2: The Vortex simulation platform with peripherals. The system is organized around a rack containing the artificial neurons chips. The control software runs on a PC. To run hybrid networks experiments, artificial neurons are connected to biological neurons via an electrophysiology amplifier.

Results:

We illustrate the use of analog neurons in the study of the thalamus filtering properties. The thalamus is a major relay structure of the brain where most sensory pathways (visual, somatosensory, auditory…) are relayed to cerebral cortex. This position allows the thalamus to filter or faithfully transmit sensory information depending on the state of arousal (sleep, awake). To study how this sensory gating is performed, we have investigated the interaction between three cell types in the visual thalamus: the thalamocortical neurons (TC) that relay sensory inputs from the retina, local inhibitory interneurons (nRt) and an input neuron simulating a ganglion cell from the retina. In the brain, the TC and nRt cells populations are reciprocally connected through excitatory (TC to nRt) and inhibitory (nRt to TC) synapses. This circuit forming a feedback loop was modeled in real-time using analog circuits and was used to study the role of oscillations on information transfer by the visual thalamus. Figure 3 shows a simulation, using the analog neurons, of the TC-nRt loop; the TC and nRt neurons are respectively modeled by a set of 5 and 4 conductances [2], including calcium-dependence, while synapses are also modeled by non-linear conductances.

It appeared in simulations that changes in the synaptic gains did affect the temporal correlation between nRt spikes and TC spikes, thus offering a mechanism for spike transfer control. The validity of this type of hypothesis was recently tested by the reconstruction of "hybrid circuits" mixing biological and artificial neurons connected through artificials synapses in slices *in vitro* [3]. In the figure 4, a biological thalamic neuron receives synaptic inputs from two different types of artificial neurons, one of which, a model retinal cell, is implemented on analog circuits and connects the biological TC neuron through model excitatory synapses. The synaptic currents are calculated in real-time by the analog circuit and injected into the living cell using dynamic clamp and a standard current injection system. In absence of spiking activity in the models cells, the biological neuron remains in a quiescent state and does not produce action potentials (not shown). However, as shown in the figure 4, a random firing activity produced by the analog retinal ganglion cell is sufficient to trigger a background synaptic activity in the living cell resulting in the emergence of self-organized rhythmic spiking activity very similar to specific thalamic sleep rhythms (for details see reference 3). We have used this hybrid circuit and its property to generate emergent state, to

test the effect of systematically varying synaptic weights on the probability that spikes produced by the retinal cell triggered output spikes in the relay thalamic cell. We found that increasing the feedback inhibition from nRt cell to TC cells dramatically reduced the retinal spikes transfer resulting in a functional uncoupling of the retinal cell.

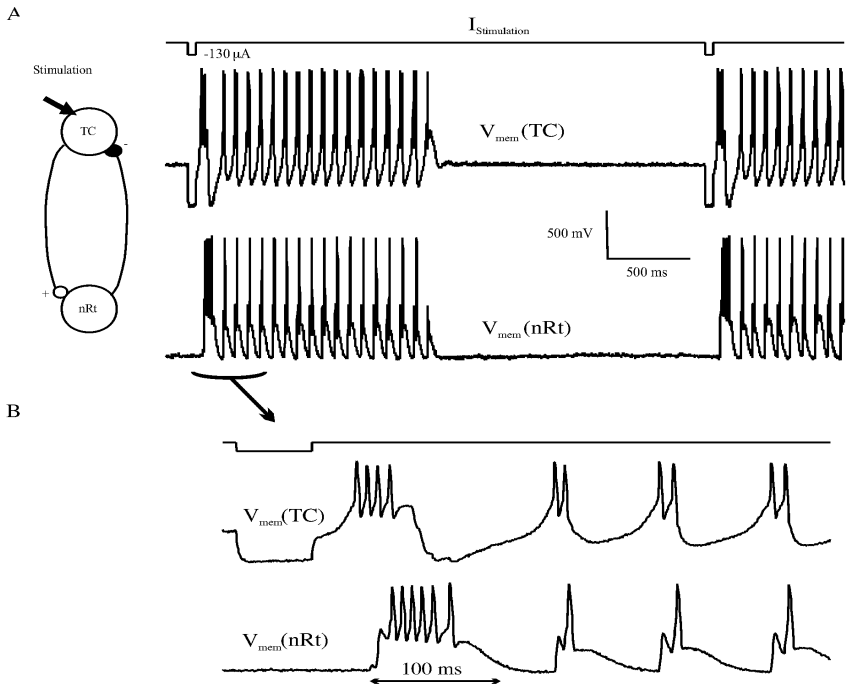

Figure 3: A: When a negative current pulse is injected into a TC biological neuron the characteristic response is a rebound burst of action potential. The simulation reproduces the same pattern. When two neurons TC and nRt are synaptically coupled by and inhibitory (nRt->TC) and an excitatory synapse (TC ->nRt) the same inhibitory pulse generates a sustained oscillation until a relaxing state occurs [2]-
B: Zoom of plot A. One can observe precisely the individual action potential shape.

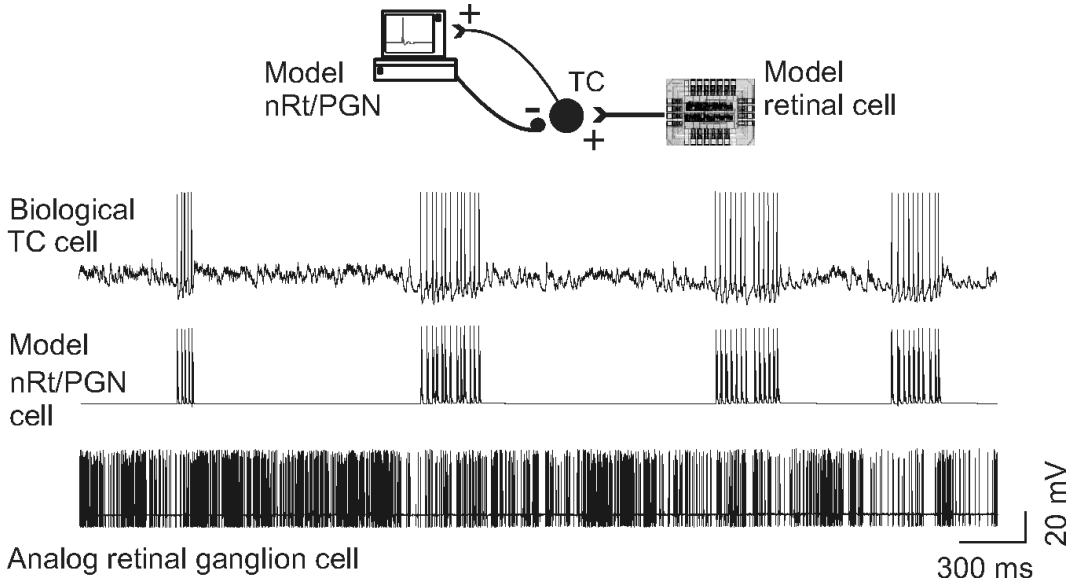

Figure 4: Emergent rhythmic activity in a hybrid circuit mixing model and biological neurons. An analog model neuron (bottom trace) was programmed to simulate the temporal structure of real retinal cell discharges and the kinetics of real AMPA receptor-mediated excitatory postsynaptic potentials (EPSPs). Hybrid thalamic circuits receiving this emulated synaptic bombardment spontaneously generated short epochs of oscillation, recurring periodically in a manner very similar to biological spindle waves occurring in sleep.

Developments:

We next present a new tool, which is currently developed to address neural computation at the network level. We designed a mixed analog-digital architecture in which all membrane equations including synaptic integration are solved by analog ASIC circuits, while the connectivity is managed by a digital interface. Analog neurons are similar to the ASIC circuits described above, except that the model parameters are limited to a few configurations (excitatory and inhibitory neurons based on Hodgkin-Huxley type kinetics). Synaptic interactions are modeled using simple "monoexponential" synapses (kinetics from [4]) where the synaptic conductance increases instantaneously of a given "quantal conductance" when a presynaptic spike occurs, then relaxes exponentially to zero. The neural activity and the presynaptic information are digitally coded; the digital interface reads the neuron's activity (spikes), and dispatches them as inputs to other neurons according to the programmable connection matrix. The digital interface can also manage in real time low-level plasticity rules, which dynamically modify the connectivity and the quantum weights. The main advantage is flexibility: different types of connectivity can be tested, as well as different types of plasticity rules (also managed by the digital interface). The system can also be used to implement probabilistic release and short-term plasticity.

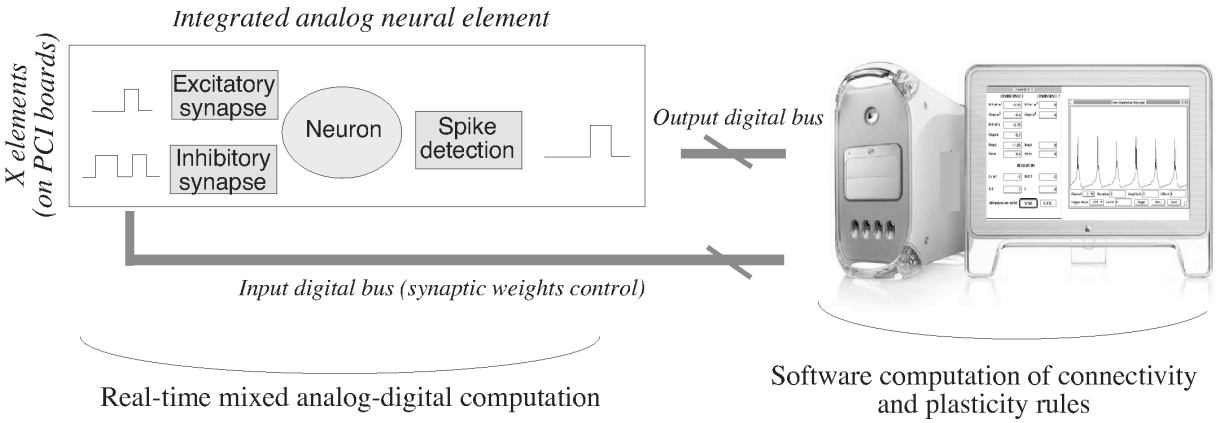

Figure 5: Hardware/software structure of the mixed analog-digital simulation system. Neural elements are analog integrated circuits, on electronics boards (X neural elements per board, X depending on the ASIC version). A PCI interface allows digital transfer between the circuits and a custom software. A real-time software/hardware closed loop processes the neuronal spikes and dynamically controls synaptic quantum and connectivity updates.

This type of analog-digital system is dedicated to the simulation of networks of conductance-based neurons. For example, cortical microcircuits consisting of Hodgkin-Huxley neurons of regular-spiking and fast-spiking cortical neurons, interconnected using glutamatergic (AMPA, NMDA) and GABAergic (GABA-A) synapses, can be simulated using this system. The digital interface offers flexibility about the dynamics of synaptic interactions: mechanisms such as short-term synaptic depression or facilitation, long-term potentiation or depression, or even spike-time dependent plasticity [5], can be incorporated using the same system (work in progress).

Conclusion:

We showed here that our ASIC circuits can provide useful tools for computational neuroscience, both at the single-cell and network levels, such as the confinement of models of spiking neurons and synaptic plasticity, with mechanisms such as simple weight updates, or

more complex algorithms such as spike-timing dependent synaptic plasticity (STDP, weight updates dependent on the temporal relation of activity). The most fascinating application is probably the possibility of interfacing single neurons - or networks of neurons - to intracellularly-recorded neurons in slices or even in vivo. Such applications necessarily require models simulated in real time, in which case the present approach can be extremely useful. Analog emulation is an interesting alternative to digital computing for close-to-biology modelling and for computational applications close to experiments. On-chip analog computation is not very commonly developed, and is dedicated to very specific applications. Mixed analog-digital architectures intending to exploit best of both worlds may be interesting solutions for large networks where there is no absolute necessity for real-time simulation, except for the input and output neuron layers that may communicate with biological neurons.

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***Note** Research is supported by CNRS, INSERM and the European Community (Future and Emerging Technologies).*