The BioRC Biomimetic Real-Time Cortex Project

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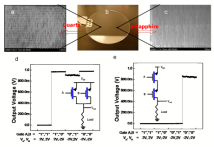
Introduction

- Central objective: design, simulation and construction of nanocircuits that model portions of the human cortex
- **Exploit the analog computational power of transistor circuits to meet complexity challenges**
- Use carbon nanotubes and nanowires as the candidate nanotechnology to meet scale challenges as well as prosthetic advantages

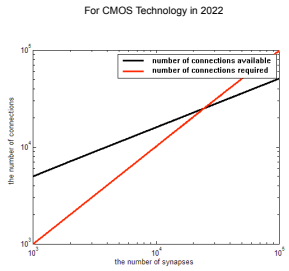


•**Carbon nanotube fabrication by Chongwu Zhou**
Aligned nanotubes and resulting logic gates

Engineering Challenges for a Synthetic Cortex

•**Complexity**:
Synaptic mechanisms - excitatory and inhibitory synapses
Dendritic computations and dendritic spikes
•**Scale**:
100 x 10^9 neurons and 10^4 to 10^5 synapses/neuron
~100 transistors/synapse including dendritic computations
CMOS neurons for a cortex, absent interconnection area, could occupy an entire room, even in 2021
•**Connectivity**:
Fan-in/neuron 10^4 to 10^5 distinct connections; Fan-out 10^4
Address space 37 bits (assuming synaptic inputs are distinct)
•**Plasticity**:
New neural connections form within hours
Presynaptic depression/facilitation occur
Postsynaptic depression and potentiation occur

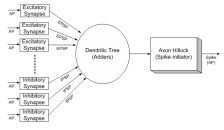
Connectivity as a function of Neuron Size



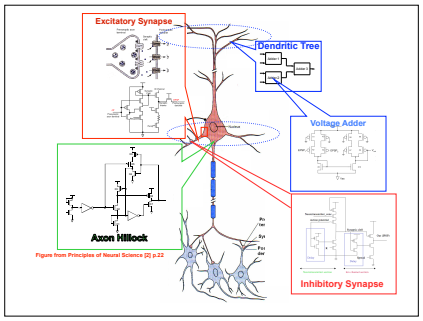
The Basic Central Neuron Architecture

The whole neuron can be divided into these sub-circuits:

- **Synapse**
  - Excitatory/Inhibitory synapse circuit (Action Potential as inputs and EPSP/IPSP as outputs)
- **Dendritic Tree**
  - A pool of voltage adders (which can add two input stimuli in both linear or non-linear ways)
- **Axon Hillock**
  - Amplifier (in order to reach the threshold of carbon nanotube FET)
  - Spike-initiator (Action Potentials are all-or-none)



The Biomimetic Neural Circuits



Neural Circuit Designs Completed

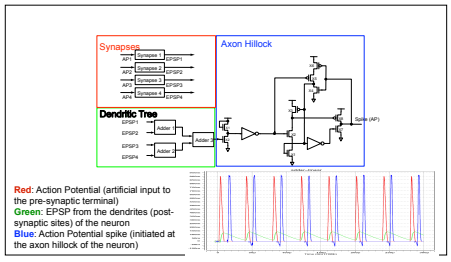
•The **excitatory and inhibitory synapse circuits** model
- ❖ an action potential applied to a biological synapse
- ❖ neurotransmitter action, including
  - ◆programmable transmitter availability
  - ◆ programmable ion channel receptors
  - ◆Programmable reuptake delay
- ❖ membrane potentials
- ❖ ion pumps
- ❖Dendrodendritic connections
- ❖Shunting and hyperpolarizing inhibition

•The voltage adders model **sublinear, linear, and superlinear dendritic computations** involving EPSPs and IPSPs in the dendritic arbor

•**Axon hillock circuits** model action potential generation
- ◆Single spike
- ◆Burst of spikes

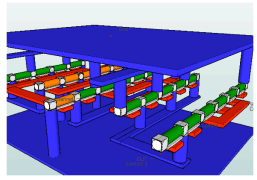
•Circuit designs favor economy of size over exact replication of waveforms, to facilitate scaling to cortical-sized neural networks, with approximate waveform shaping

A Simplified Central Neuron Circuit



Red: Action Potential (artificial input to the pre-synaptic terminal)
Green: EPSP from the dendrites (post-synaptic sites) of the neuron
Blue: Action Potential spike (initiated at the axon hillock of the neuron)

A Future Carbon Nanotube Synapse

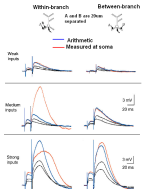


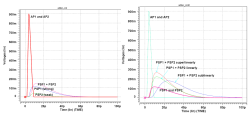
Dendritic Computations

❖Mel, Schiller *et al.*: results of EPSP summation at soma of layer-5 pyramidal neuron with respect to within-branch and between-branch stimulations

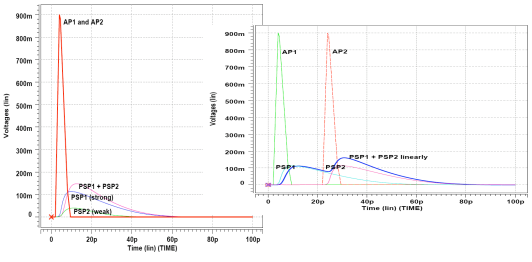
❖Between-branch EPSP summation linear for weak and medium stimuli and slightly superlinear for strong stimuli.

❖Within-branch EPSP summation shows both linearity and non-linearity depending on the strength of EPSP.





Addition of EPSP's



The BioRC Project Team and Support

•Alice Parker, PI and Chongwu Zhou, Co-PI
•Graduate Assistants
Chih-Chieh Hsu - CNT circuits and simulation
Jonathan Joshi - CMOS circuits and simulation
Ko-Chung Tseng - Mathematical models of interconnectivity
Chuan Wang - Carbon nanotube fabrication
Adi Azar - Neural architecture
Khushnood Irani - 3-D circuit visualization
Jason Mahvash - analog circuits
Matthew Walker – Nano-interconnections/assembly
Numerous directed research students

•Support for this research has been provided by the Viterbi School of Engineering and the WiSE Program at USC and NSF Grant 0726815.

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