Biomimetic Cortical Nanocircuits: The BioRC Project

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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
- Affiliated Students
  - Adi Azar - Neural architecture
  - Khushnood Irani - 3-D circuit visualization
  - Jason Mahvash - analog circuits
  - Numerous directed research students

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Project Motivation: Challenges for a Synthetic Cortex

- Complexity:
  - Synaptic mechanisms - excitatory and inhibitory synapses
  - Dendritic computations and dendritic spikes
  - Quantum stochastic behavior of neurotransmitter release

- Scale:
  - 100 x 10^9 neurons
  - 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
Meeting the Challenges for a Synthetic Cortex

- **Complexity:**
  - Exploit the analog computational power of transistor circuits

- **Scale:**
  - Consider nanotechnological solutions - nanotubes, nanowires, graphene, quantum dots

- **Connectivity:**
  - 3-D structure probably required

- **Plasticity:**
  - Add transistors as “knobs” to control neural behavior
  - Self-assembly, using a protein gel to provide scaffolding, and synthetic DNA to assemble/reconfigure neural circuits

- **We are very far from a synthetic human cortex, but it may be possible in the coming decades**
Results to Date

• Carbon nanotube fabrication (Chongwu Zhou)
  • Aligned nanotubes, logic gates

![Diagram showing experimental setup and graphs representing output voltage.]
Artist’s Conception of 3-D Carbon Nanotube Synapse
Biomimetic Neural Circuits

Figure from Principles of Neural Science [2] p.22
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)
Results to Date: A Carbon Nanotube Synapse
Results to Date: A Carbon Nanotube Synapse
Results to Date: A CMOS Inhibitory Synapse
IPSPs with varying amounts of released neurotransmitter
Dendritic Computations

Linear or Non-linear summation

- Schiller et al. compared the measured and arithmetic results of EPSP summation at soma of layer-5 pyramidal neuron with respect to within-branch and between-branch stimulations.
- It appears that between-branch EPSP summation is linear for weak and medium stimuli and slightly superlinear for strong stimuli.
- On the other hand, within-branch EPSP summation shows both linearity and non-linearity depending on the strength of EPSP. It was linear – weak EPSP (~<1mV), superlinear – medium EPSP (1~3mV), sublinear – strong EPSP (3~10mV)

Adder structure

- Adding two inputs linearly, sublinearly, and superlinearly
Dendritic Computations with Inhibition

- **Shunting Inhibition**
  - Pulls the EPSP or the AP down to zero volts
- **Hyperpolarizing Inhibition**
  - More of a subtractive behavior

Diagram:
- Excitatory Synapse
- EPSP
- Dendritic Component
- Inhibitory Synapse
- IPSP
- Output on the dendritic tree with magnitude depending on PSP strength
Dendritic Computations with Inhibition
A Carbon Nanotube Neuron

Simplified Central Neuron Circuit

[Diagram of a simplified central neuron circuit with labels for synapses, dendritic tree, and axon hillock.]

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