A Carbon Nanotube Implementation of Temporal and Spatial Dendritic Computations

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Project Motivation: Challenges for a Synthetic Cortex

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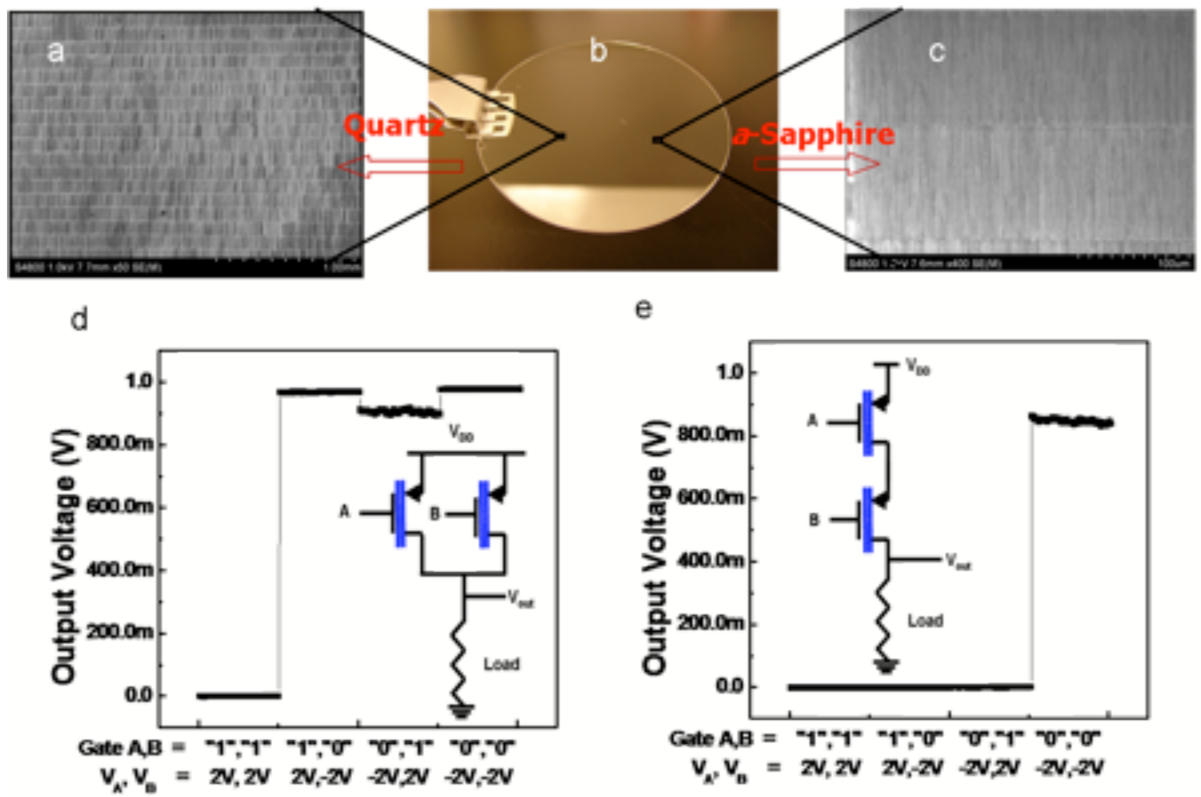
- Complexity:
  - Synaptic mechanisms - excitatory and inhibitory synapses
  - Dendritic computations and dendritic spikes
- Scale:
  - 100 x 10^9 neurons
  - 10^4 to 10^5 synapses/neuron
  - ~100 transistors/synapse including dendritic computations
  - CMOS neurons for a cortex, absent interconnection 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

- Complexity:
- **Exploit the analog computational power of transistor circuits**
- Scale:
- **Consider nanotechnological solutions - nanotubes, nanowires, graphene, quantum dots**

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**



Biomimetic Neural Circuits

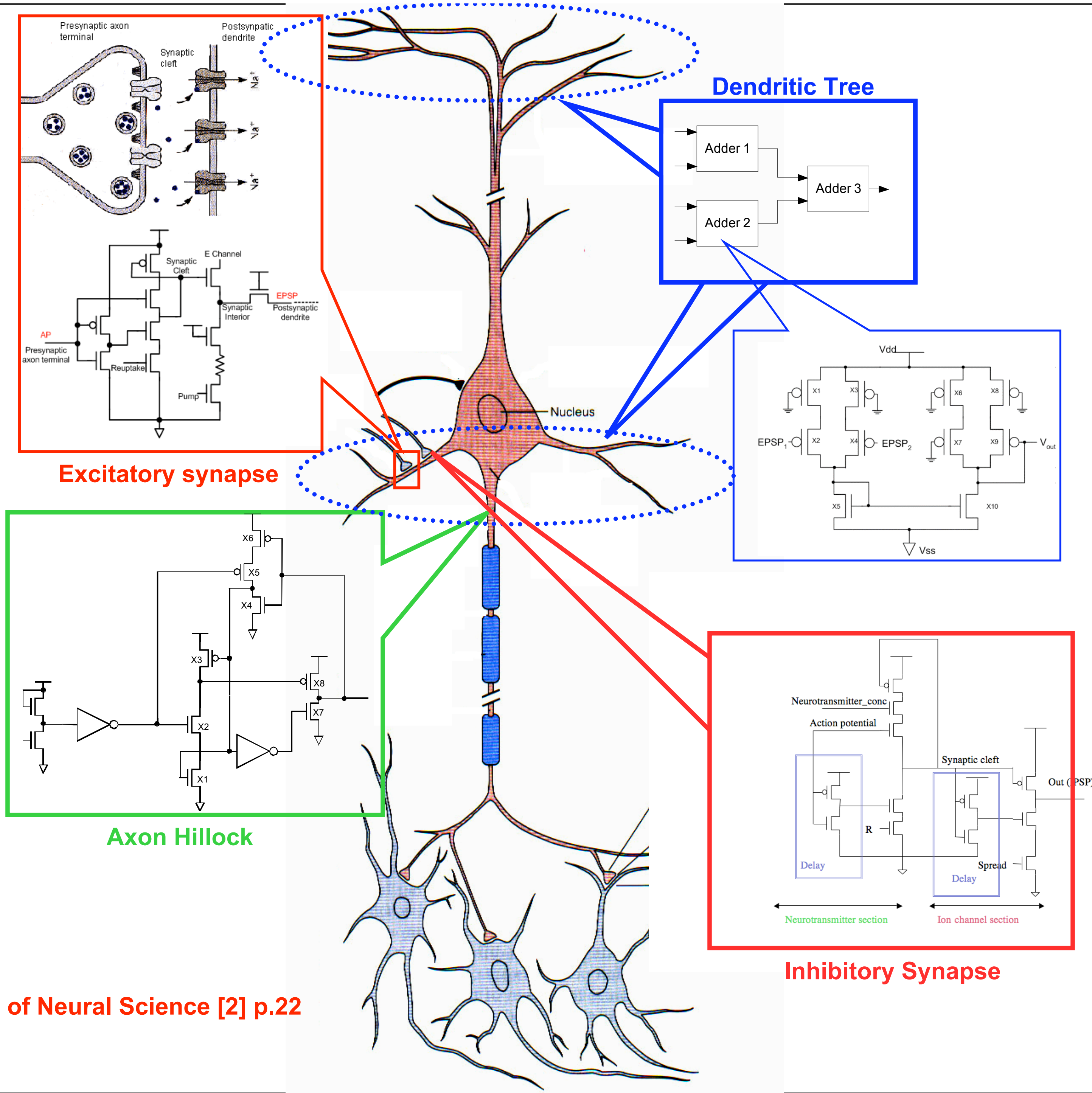
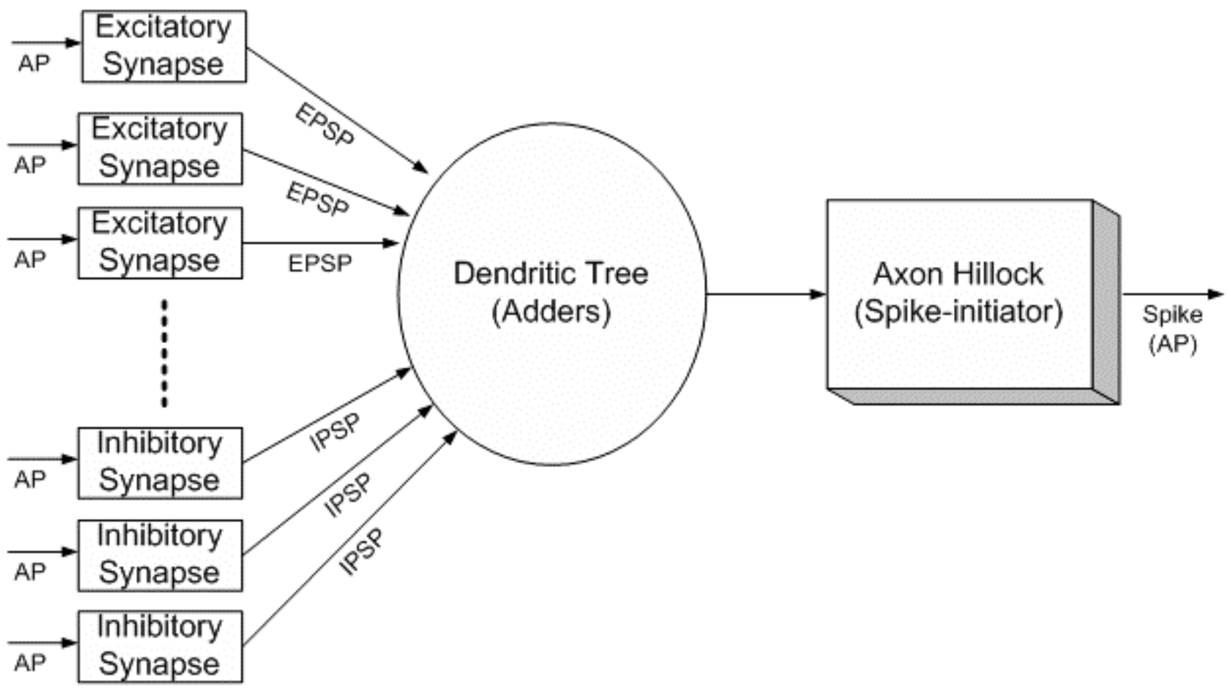


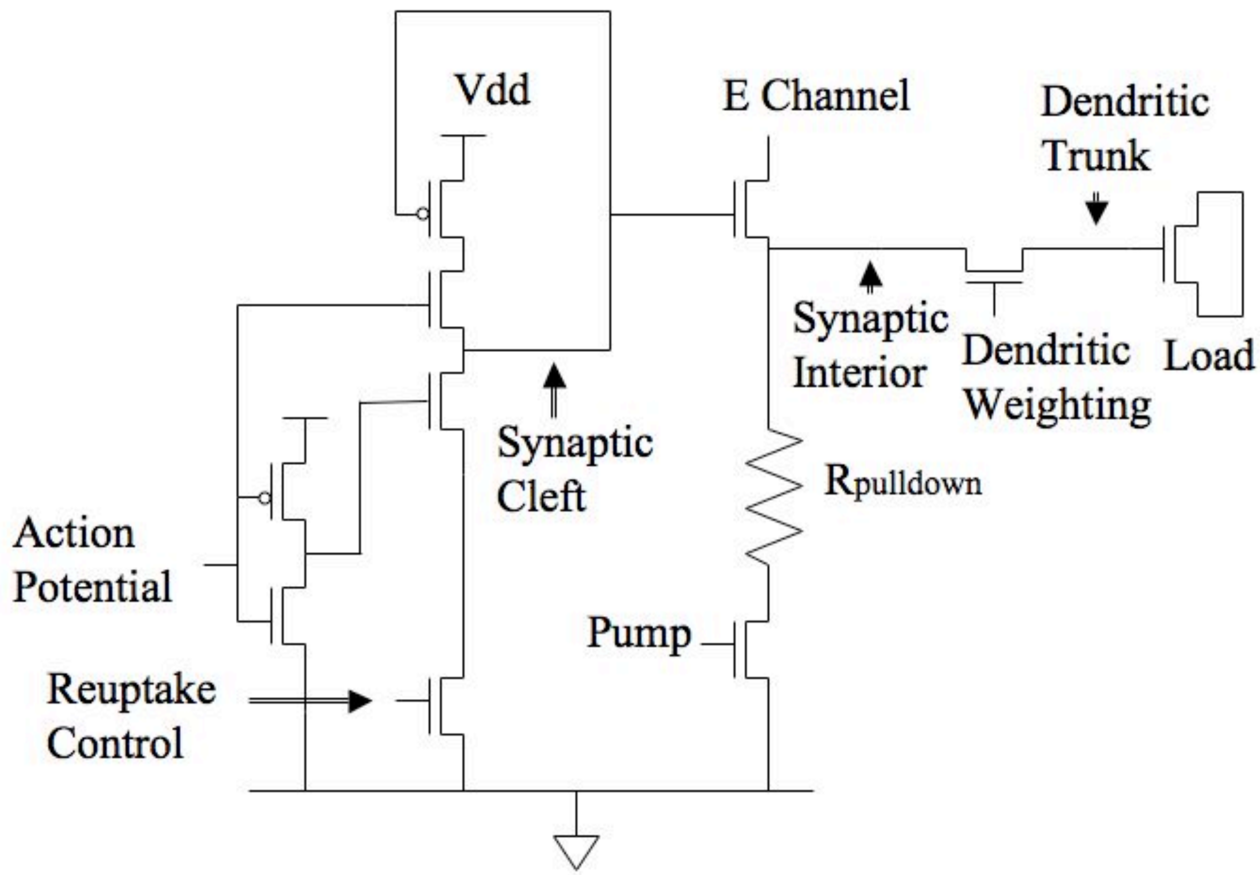
Figure from Principles of Neural Science [2] p.22

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)



A Carbon Nanotube Synapse



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Artist's Conception of 3-D Carbon Nanotube Synapse

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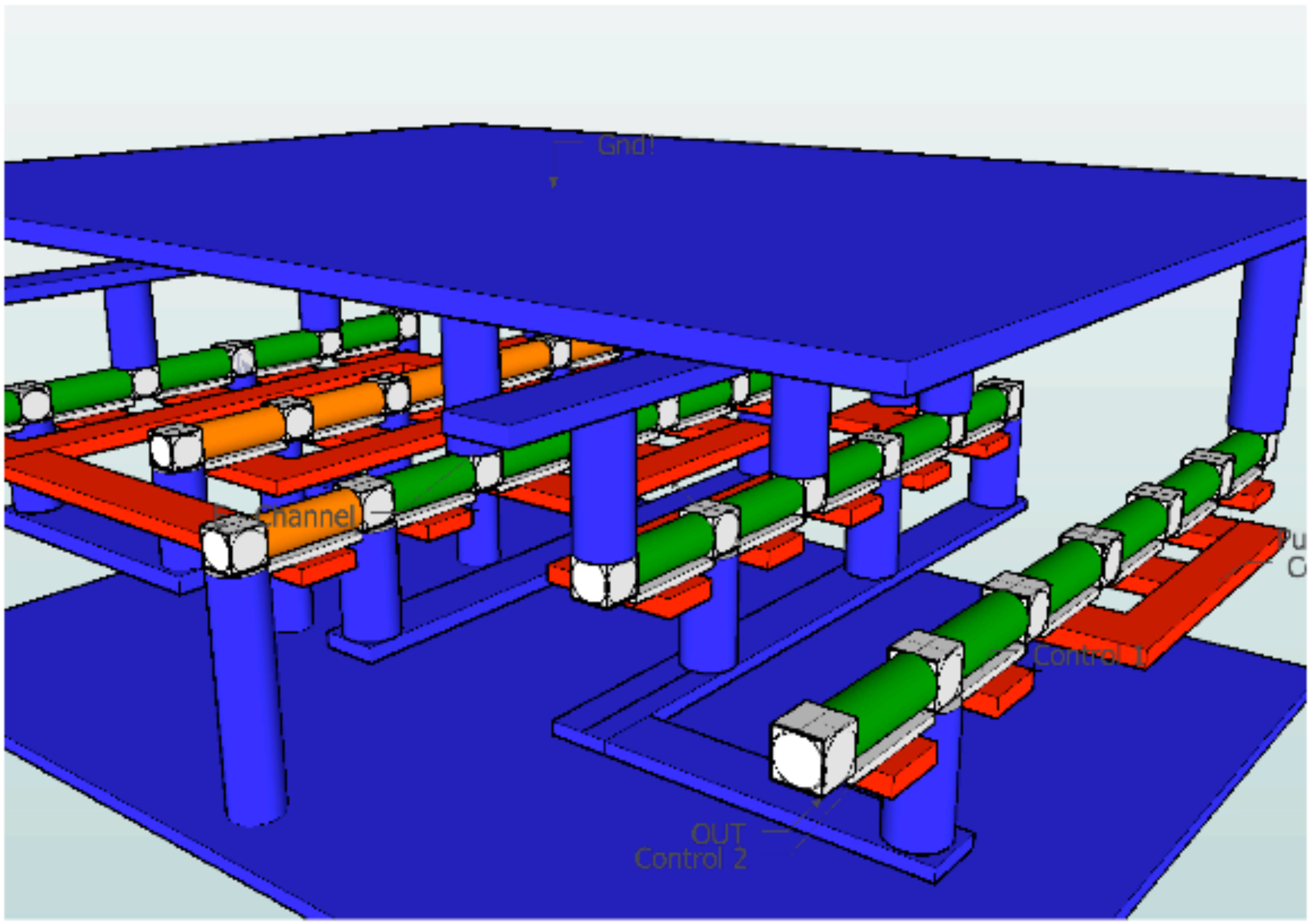
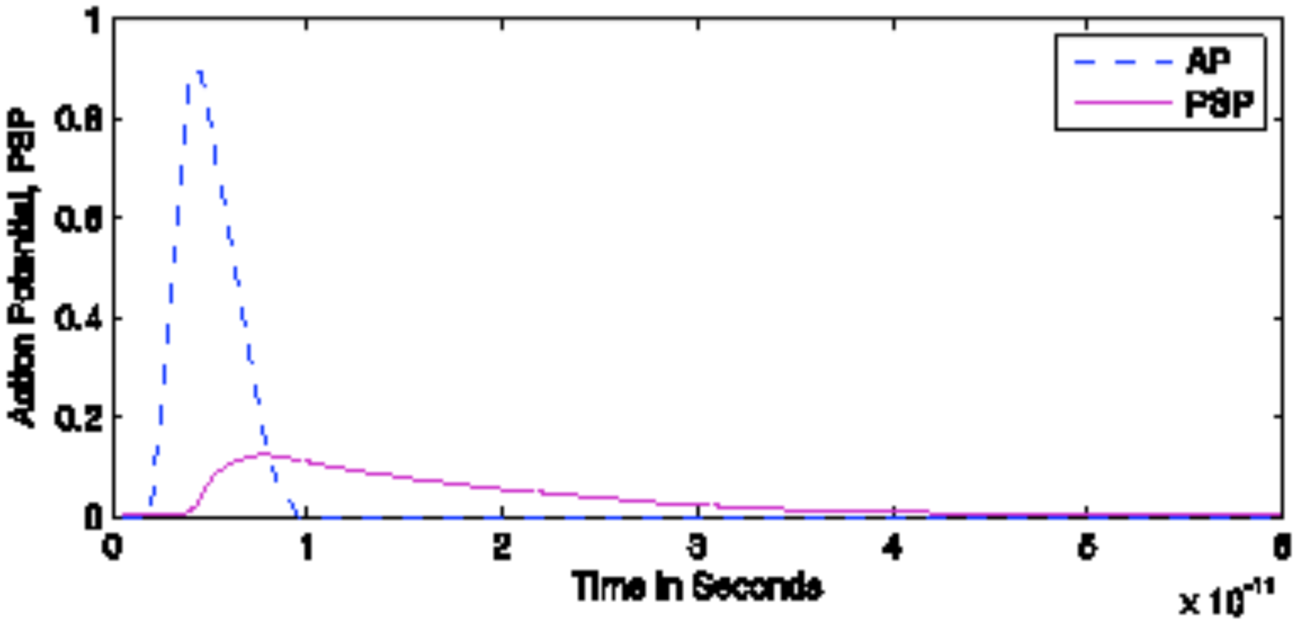


Carbon Nanotube Synapse Waveforms



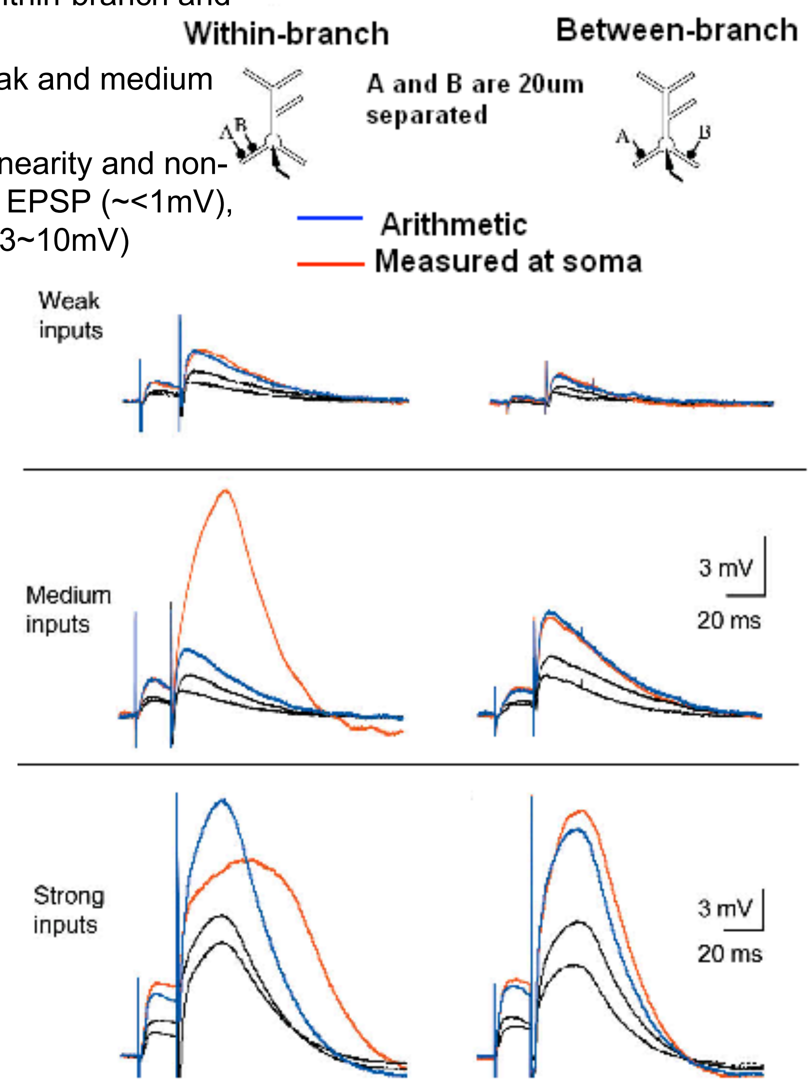
Dendritic Computations

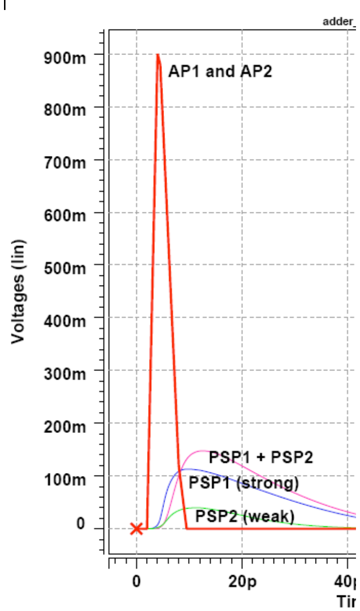
Linear or Non-linear summation

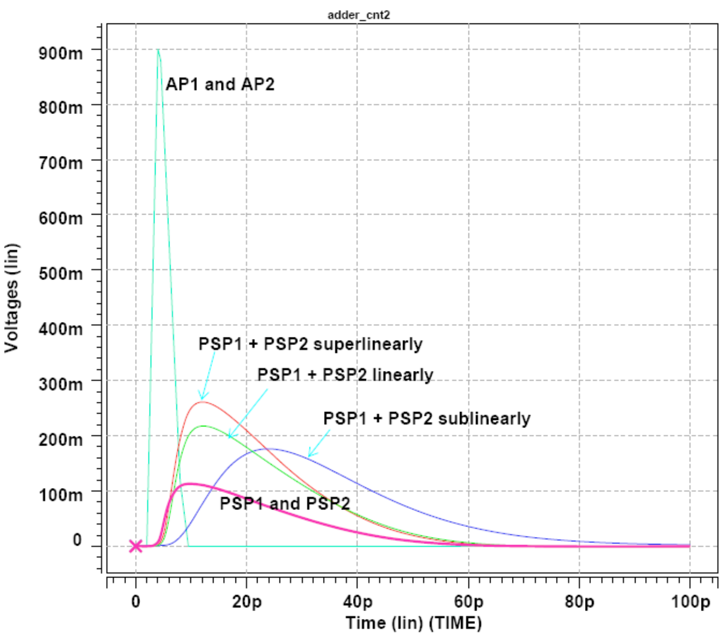
- Mel, Schiller et al. compared the measured and arithmetic results of EPSP summation at soma of layer-5 pyramidal neuron with respect to within-branch and between-branch stimulations
- It appears that between-branch EPSP summation is linear for weak and medium stimuli and slightly superlinear for strong 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

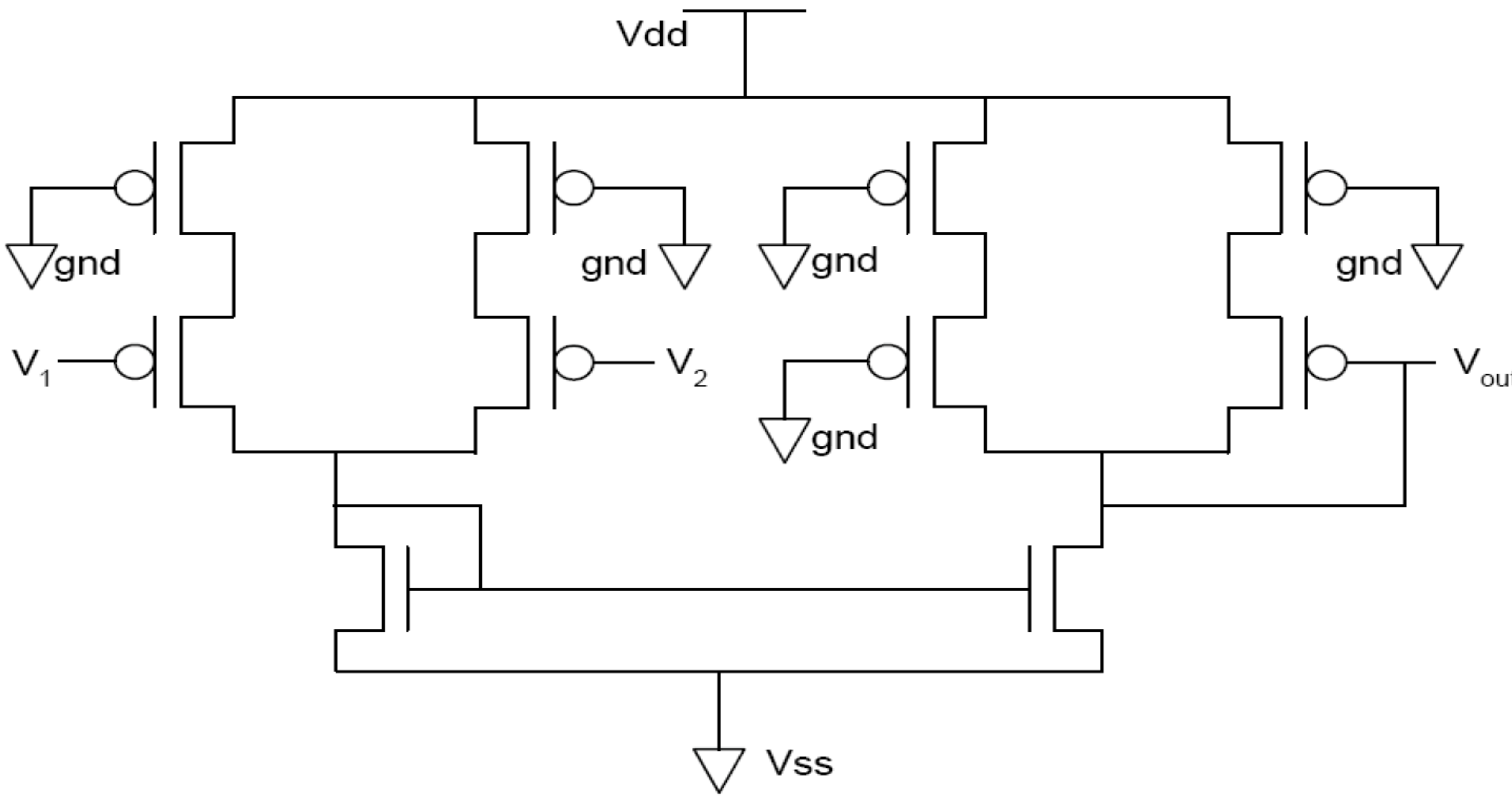
- Adding two inputs linearly, sublinearly, and superlinearly



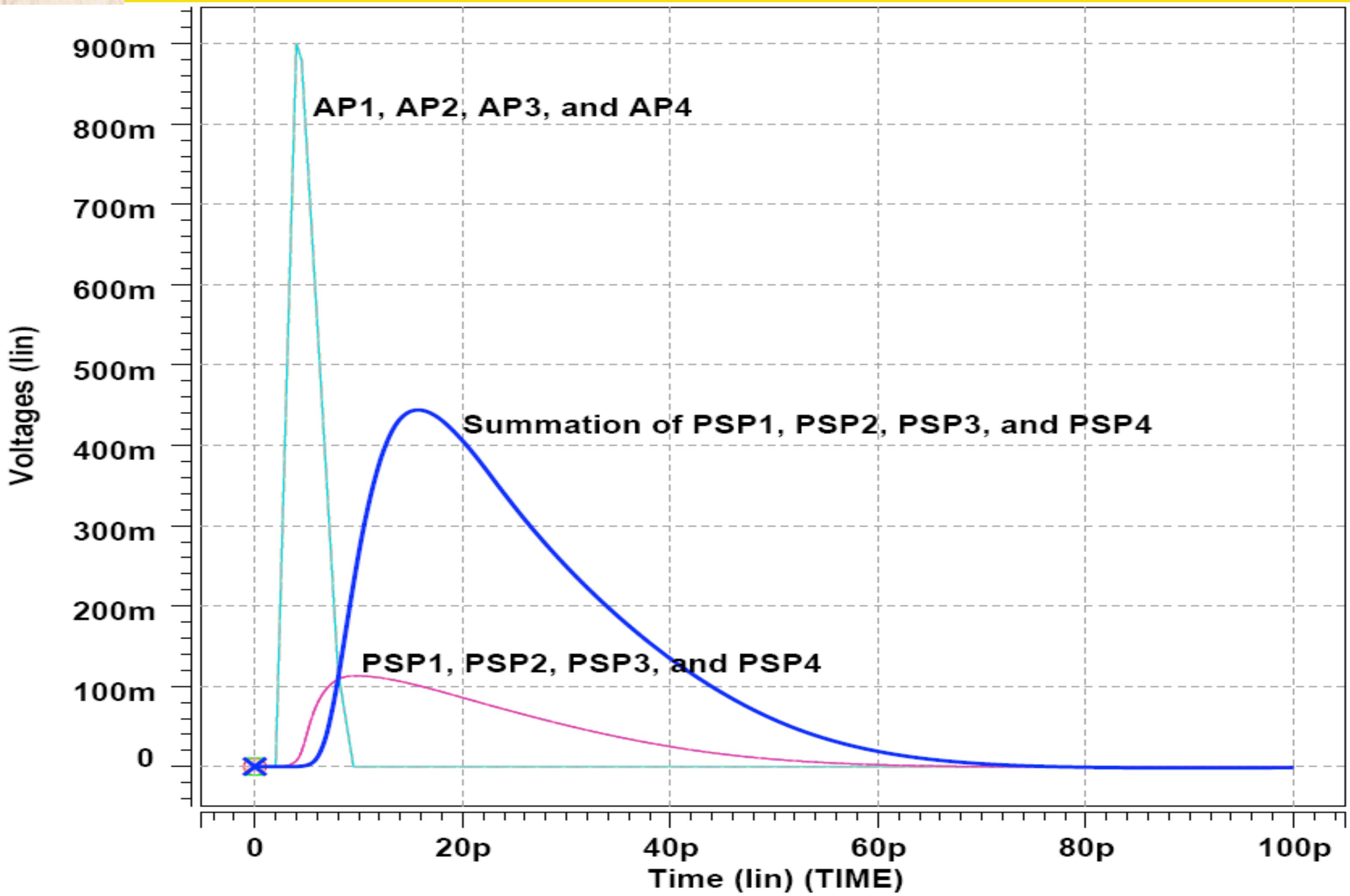




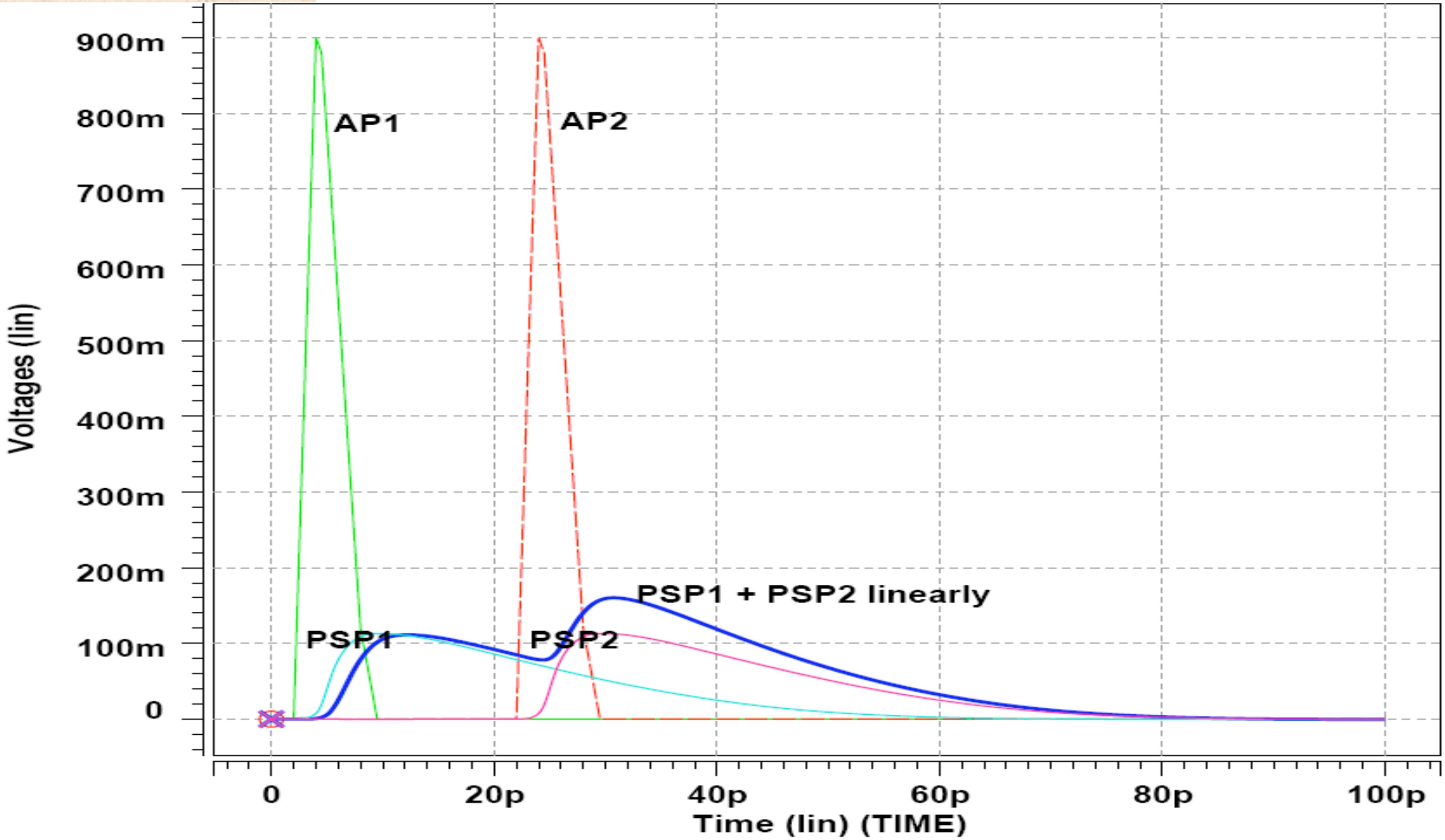
The Dendritic Voltage Adder



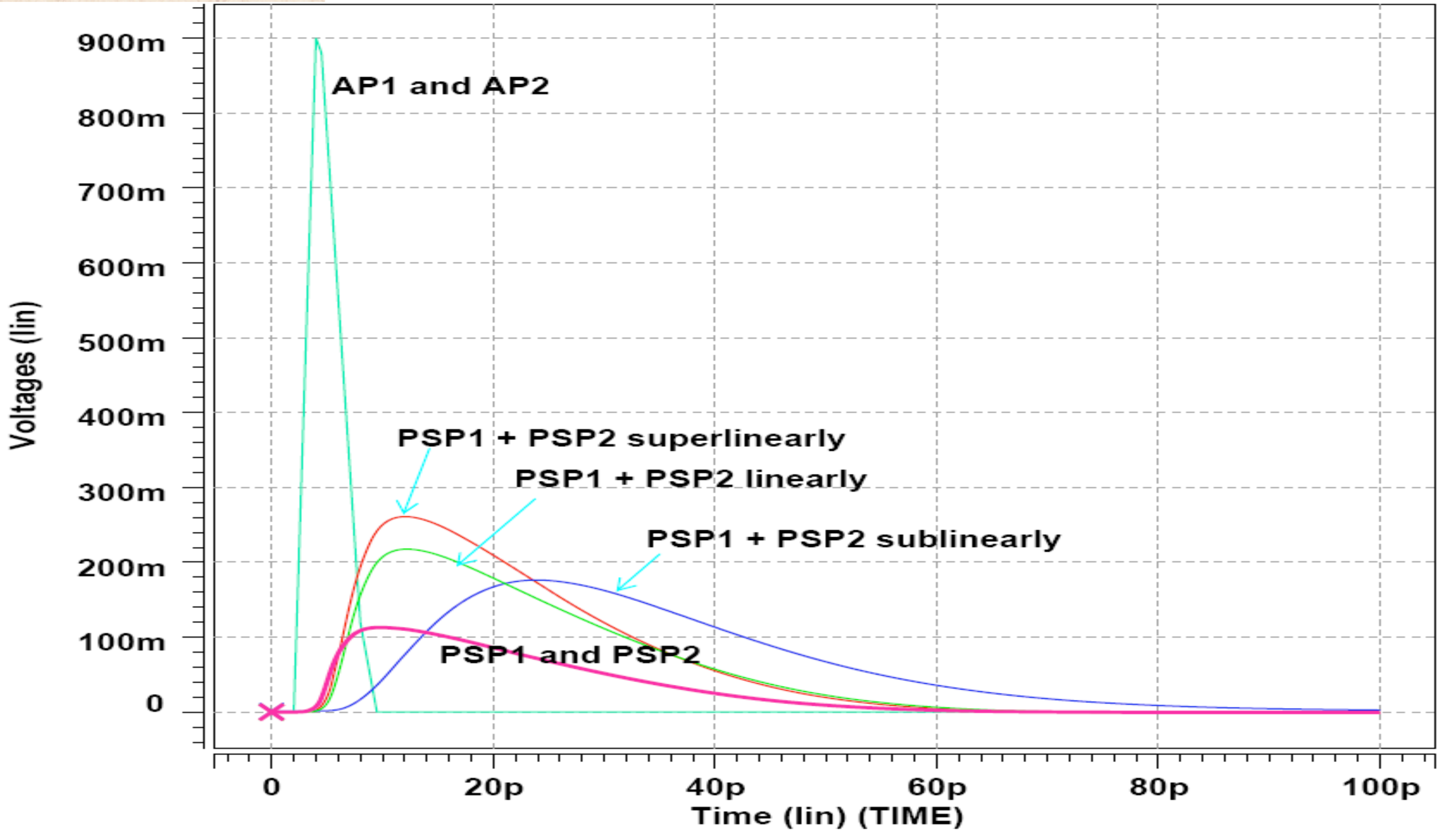
Linear Summation of 4 PSP's



Spatial and Temporal Summation of PSP's



Sublinear, Linear, and Superlinear Summation of PSP's



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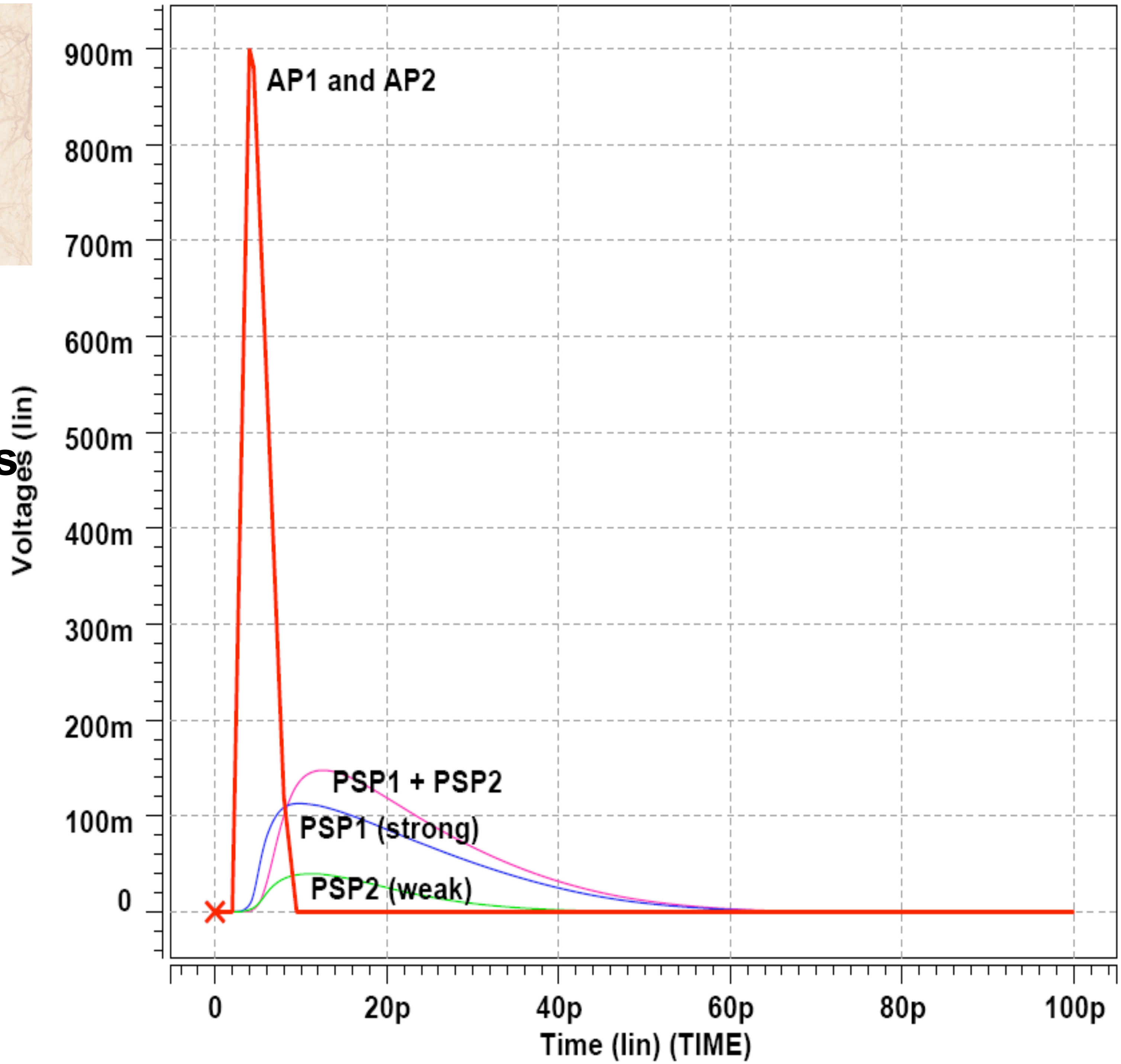
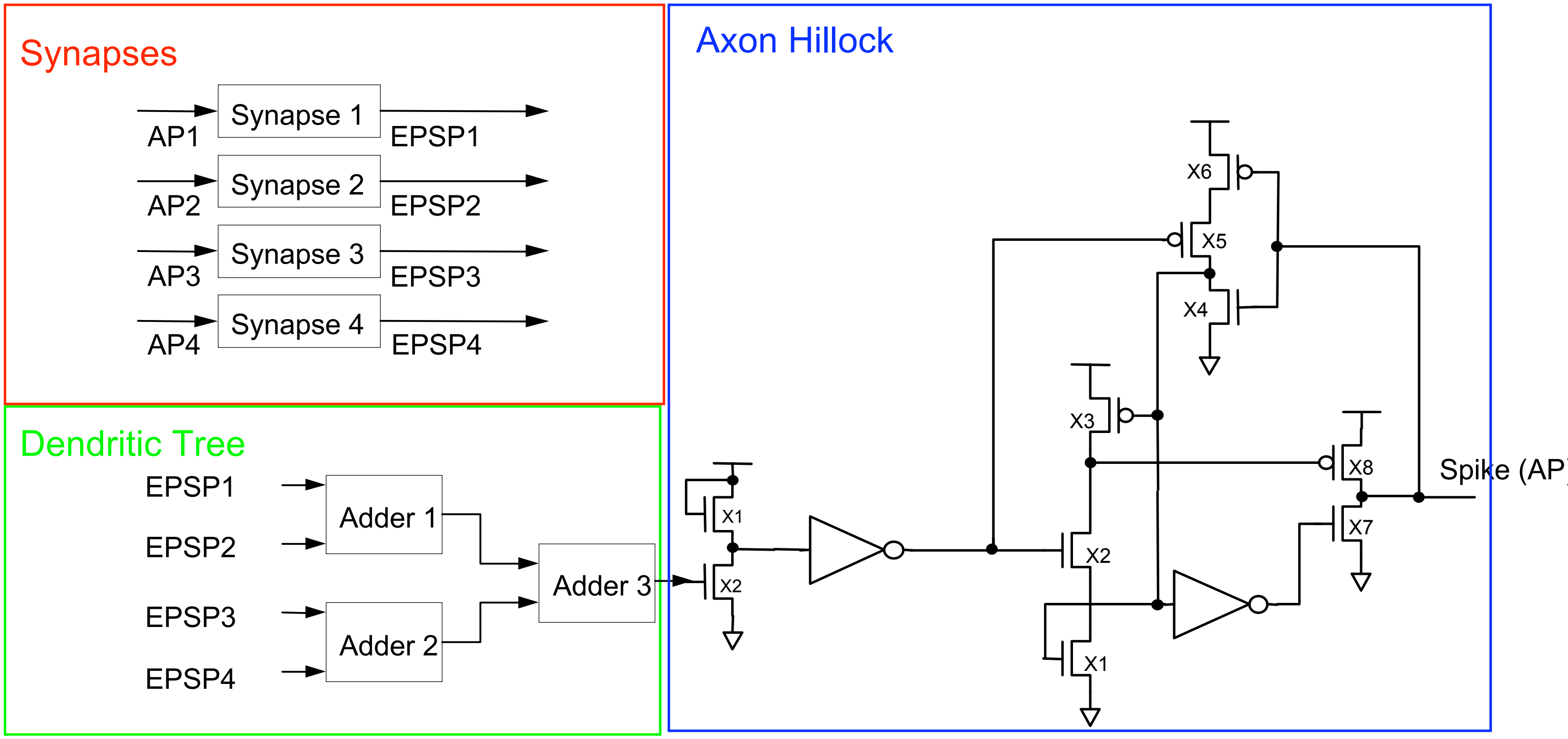
Addition of Strong and Weak PSP's



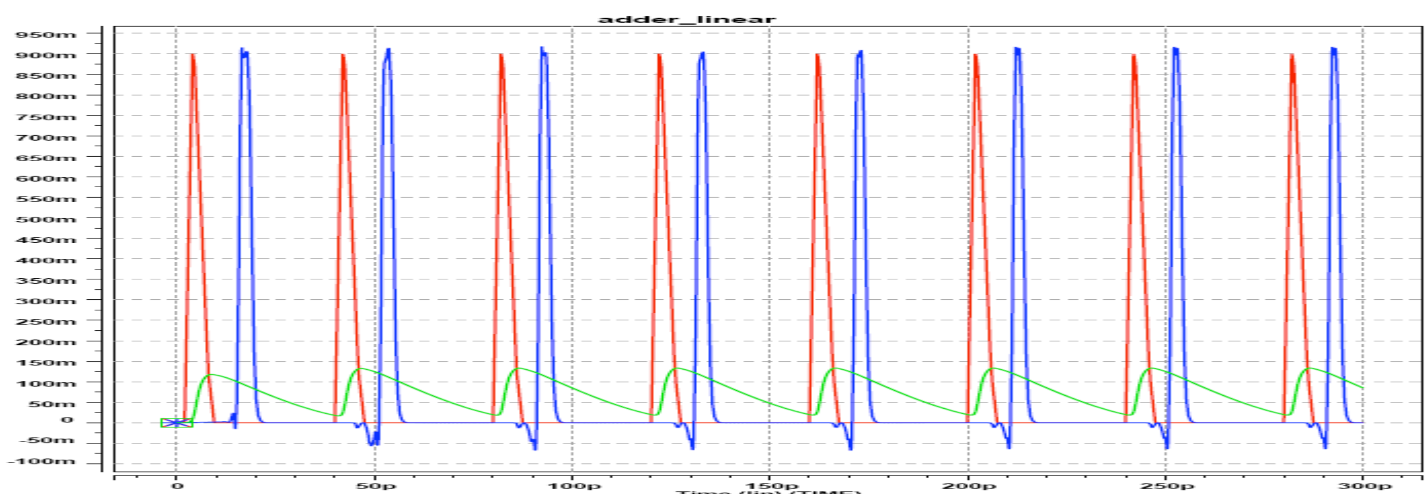
Simplified Central Neuron Circuit



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)



Conclusions

- Dendritic computations have been implemented
- A biomimetic neuron has been designed
- Carbon nanotubes pose unique challenges for analog/pulse and timing circuits
  - Adjusting R for biasing and timing is tricky due to ballistic current flow and quantum resistance
  - Nanotube circuit fabrication is in its infancy

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The BioRC Project Team and Support

USC Viterbi School of Engineering

- 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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The End

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Thank You

http://ceng.usc.edu/~parker/BioRC_research.html