A Biomimetic Carbon Nanotube Synapse Circuit

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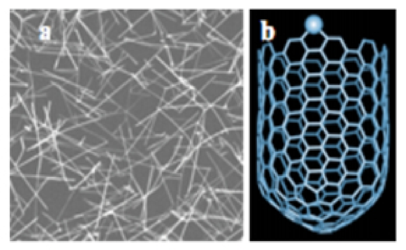
Introduction

- Central objective: design, simulation and construction of nanocircuits that model portions of the human cortex
- Use carbon nanotubes and nanowires as the candidate nanotechnology



Carbon nanowires (left) and nanotubes (right)

Engineering Challenges

- Neurons possess **complex behavior** - ion channels, dendritic computation, axons with bursts of spikes, axons with pulse trains, underlying learning mechanisms
- Cortical neurons are **highly interconnected** - 10^{13} connections - conventional electronic technologies do not support this magnitude interconnection
- New synaptic connections can form in a biological brain in hours - such **plasticity** must be supported

Value of a Synthetic Synapse

•Cortical nanocircuits could be used in **robotic systems** like autonomous vehicle control

•Could provide superior user interfaces for **speech understanding and facial recognition**

•May provide an underlying technology for **neural prosthetics** with more complex neural processing than currently envisioned systems, replacing damaged neurons

•Might further **understanding of human cortical functioning**, allowing experimentation not possible in vivo

Summary

•A neural synapse circuit using carbon nanotube transistors

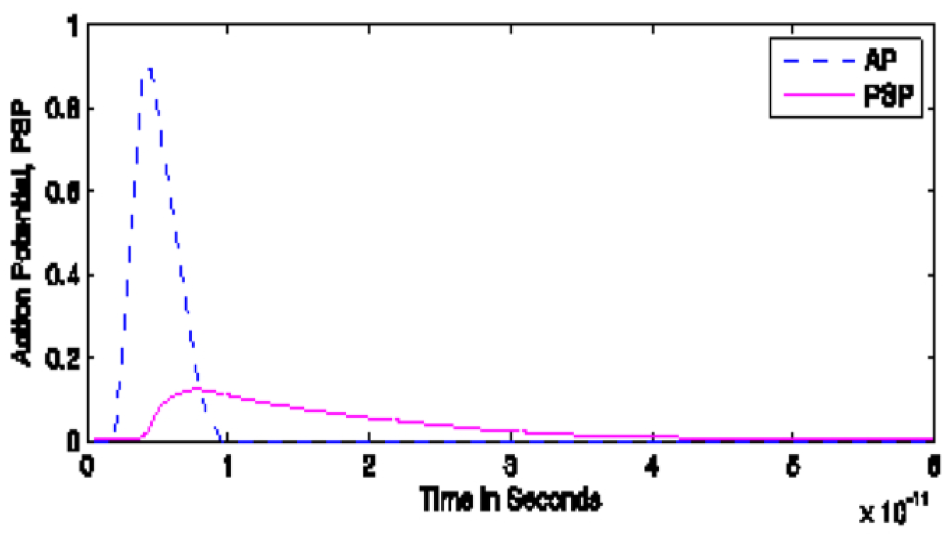
•Single-walled carbon nanotubes
- ❖avoid most of the fundamental scaling limitations of silicon devices
- ❖are an appropriate technology for a synthetic cortex

•The synapse circuit models
- ❖an action potential applied to a biological synapse
- ❖neurotransmitter action
- ❖membrane potentials
- ❖ion pumps
- ❖a reuptake mechanism that can be varied with different delays

•The circuit generates excitatory PSP's (EPSP's)

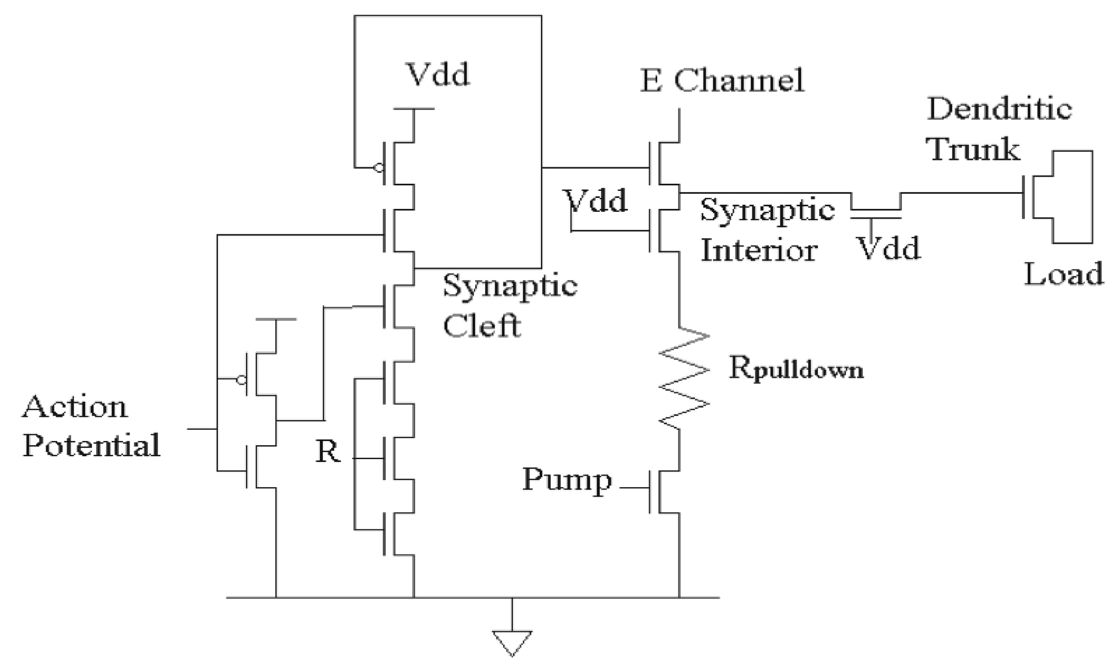
•Design favored economy of size over exact replication of waveforms, to facilitate scaling to cortical-sized neural networks

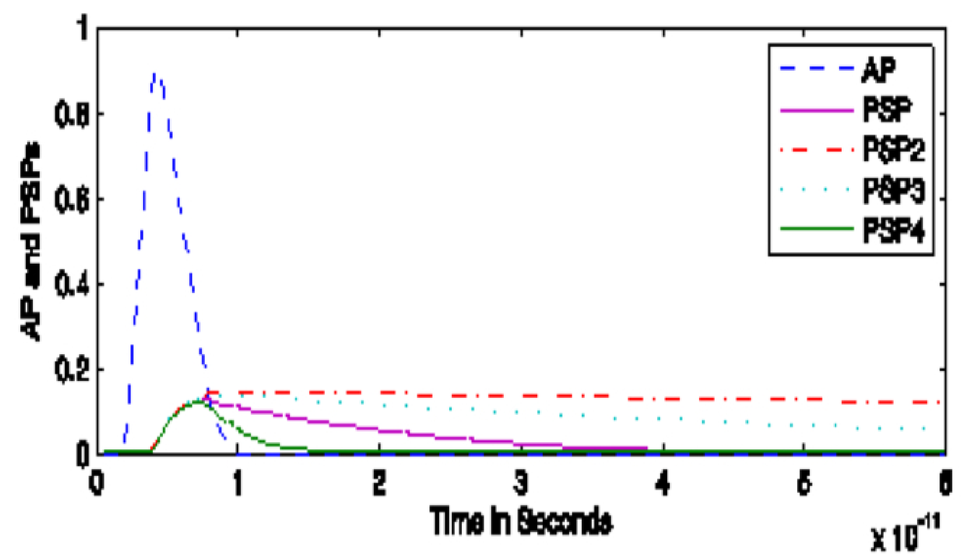
•The output of the circuit is an Excitatory PostSynaptic Potential (EPSP)



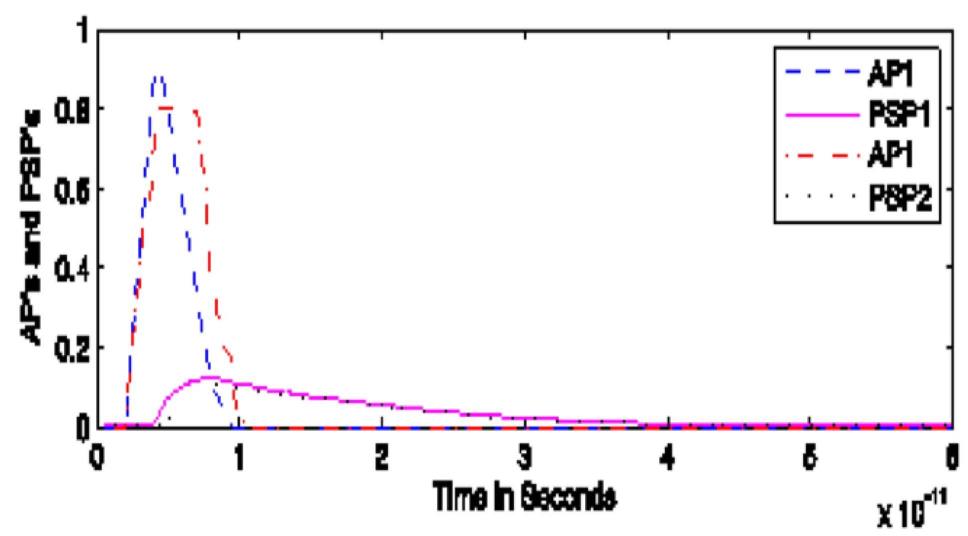
The Action Potential and PSP at the Dendritic Trunk under Normal Operation. The PSP magnitude is approximately 14% of the action potential and the duration is about 6 times as long as the action potential

The Synapse Circuit





The Action Potential and Resulting PSPs with Reuptake Control varying from 0v to .9v. We decreased the neurotransmitter reuptake control, R, to slow reuptake of the neurotransmitter and increased it to speed up the reuptake. The resultant PSP's show the greatest magnitude and longest duration PSP resulting from the lowest voltage, and the shortest, lowest magnitude PSP resulting from the maximum value of R.

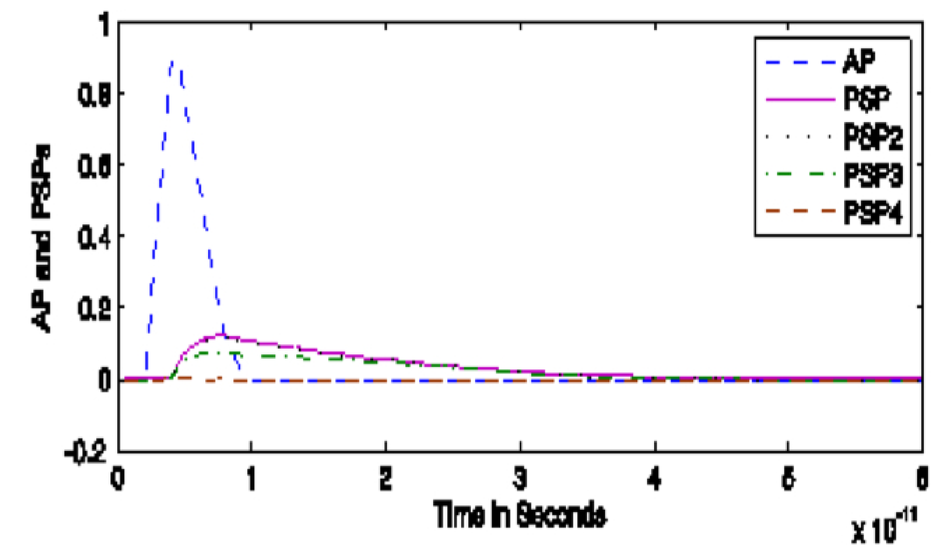


The Effect of Presynaptic Action Potential Variation on the PSP

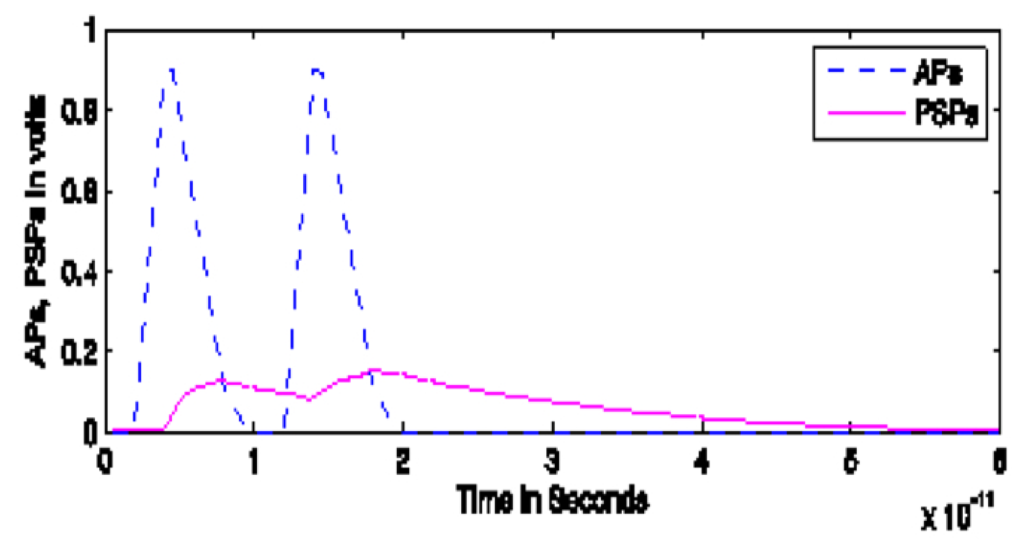
The Experiments

The circuit is simulated using carbon nanotube SPICE models

We performed simulations to demonstrate
- ❖ the synaptic response when reuptake was accelerated or delayed
- ❖ the synaptic behavior with ion channel potential variations
- ❖ temporal summation of EPSPs using multiple successive action potentials as inputs to the synaptic circuit.



The PSPs for different values of E_channel, the ion emf control. A fourth experiment shows the ability of the ion electromotive force, represented by E_Channel voltage, to control the PSP that results from ion channels opening and closing. E_Channel is varied from 0v. to .8v, and the resulting PSPs are shown. The reuptake control, R, is held at .3v, and the Pump Control voltage at .4v. The PSPs are reduced and eventually disappear when the ion electromotive force drops to 0v.



Summation of PSPs when action potentials arrive close together

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