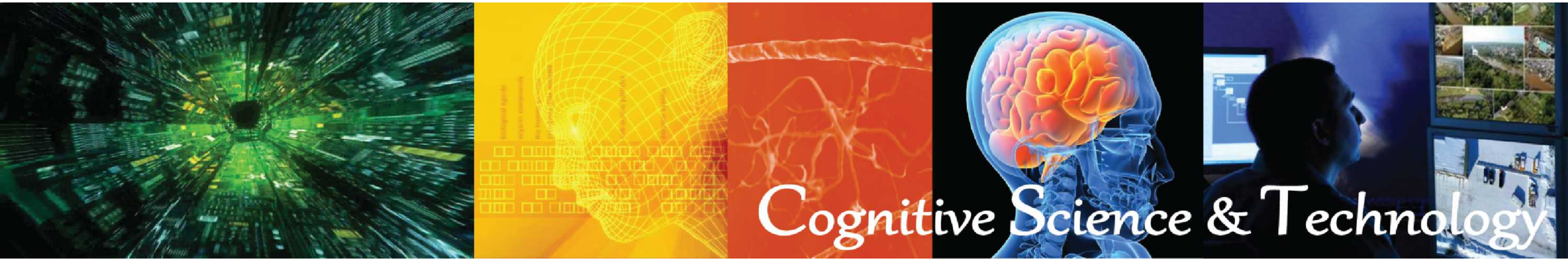
SAND2011-5953C

*Exceptional service in the national interest*

Sandia National Laboratories




# Neural Engineering and Next-Generation Electronic Computing Devices

**Conrad D. James, Ph.D.**
Biosensors & Nanomaterials -1714

August 30, 2011

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

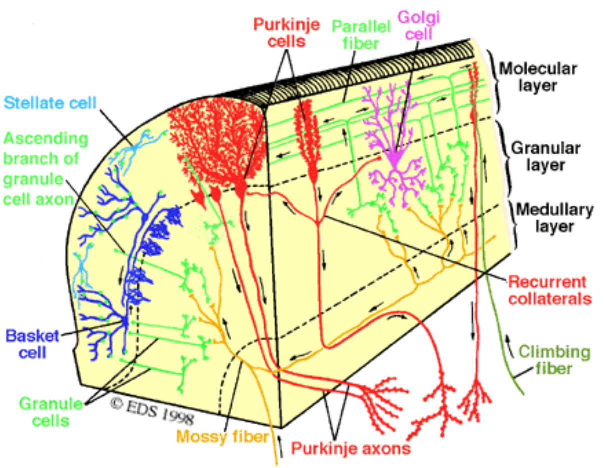
# Biological neural networks have substantial computational capabilities

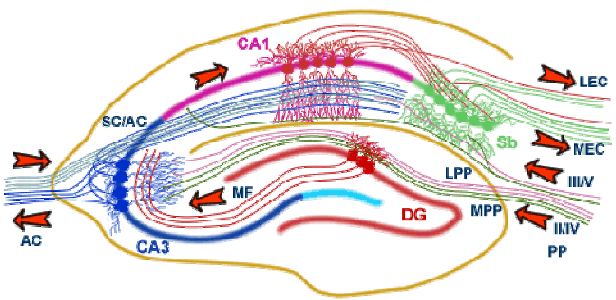

Cray XT5 Jaguar (ORNL), hex-core
~2x$10^{15}$ flops/s, **~10 MW, room-sized**
**~100 Gbits/in$^2$**
**access-limited (processor vs. memory)**

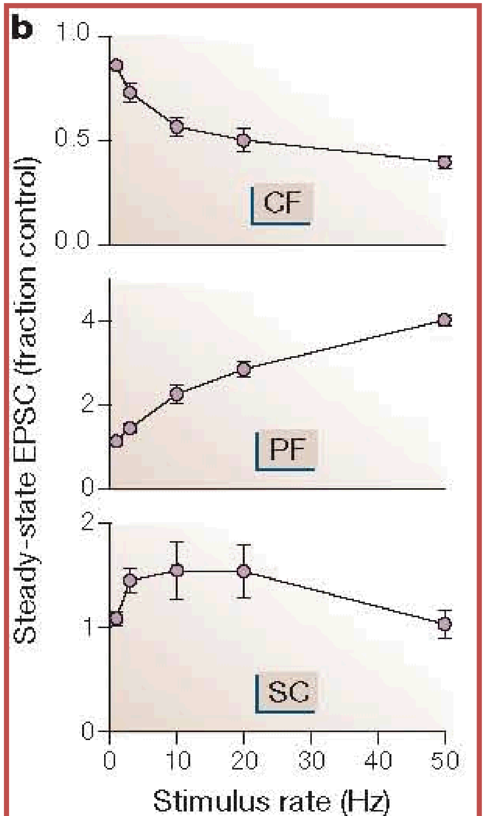
- Brain, $10^{11}$ neurons, $10^{15}$ glial cells
- >$10^{16}$ flops/s, **20W, 1200 cm$^3$**
- **~infinite memory storage capacity?**
- **near instant memory access**

1. Understand how biological networks operate
2. Implement biological computing strategies into hardware

# Influence of network architecture and stimulus frequency on network function

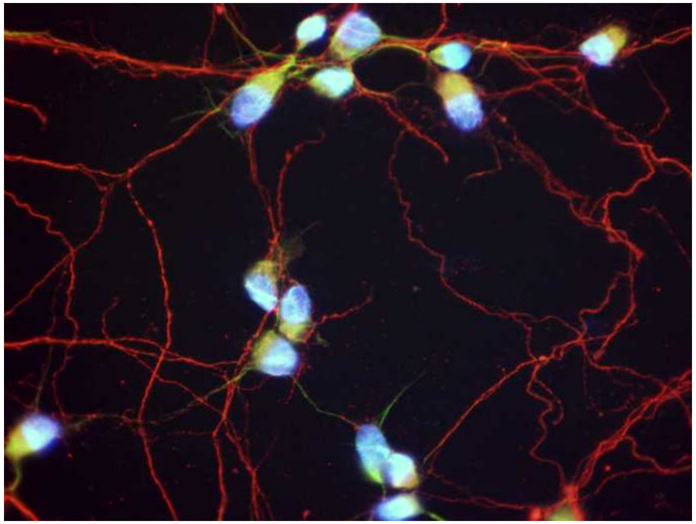


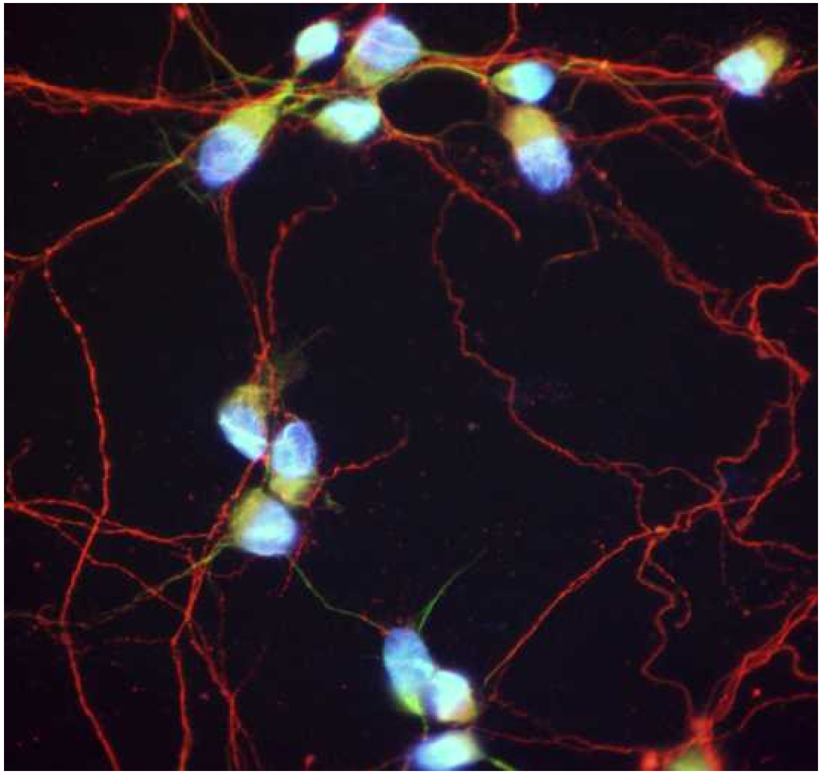



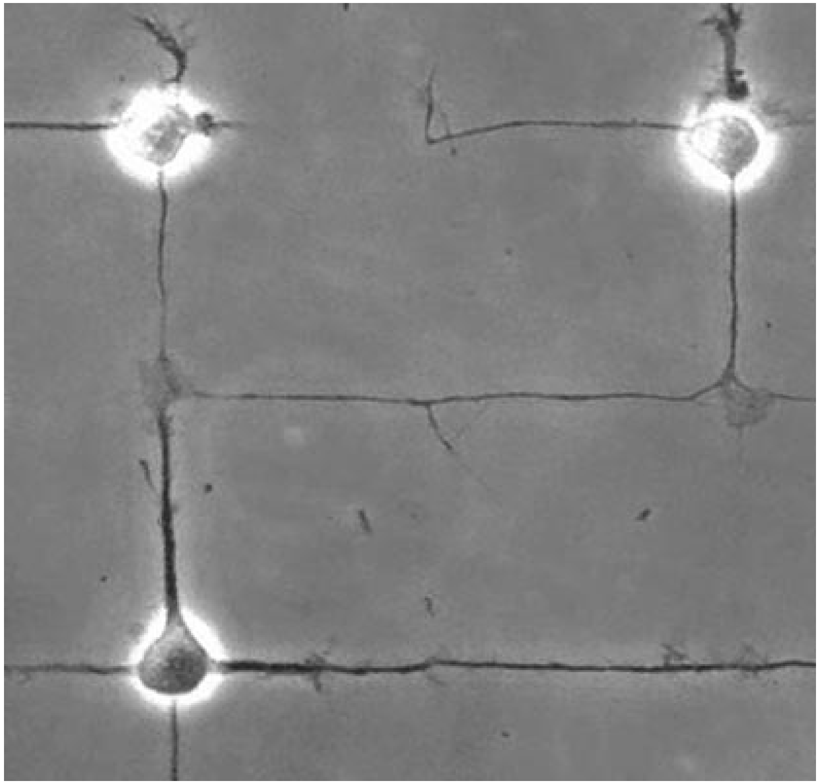

Abbot, Regehr 2004

Re-engineer dissociated neurons into networks to examine the effect of architecture on function



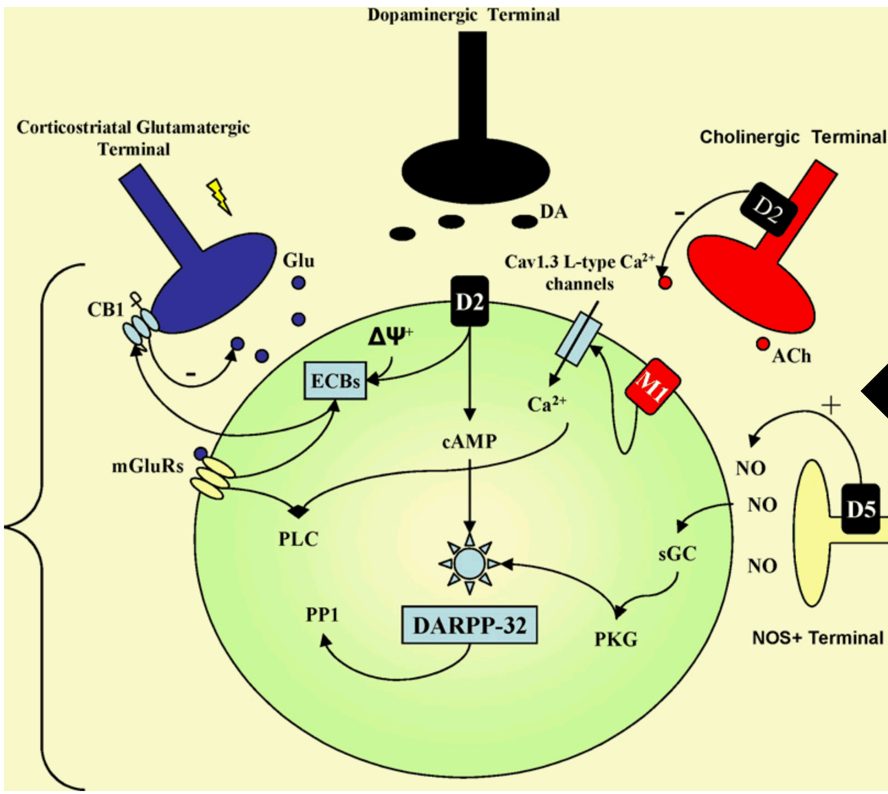
# Objective 1: Use microfabrication techniques to engineer living neural networks

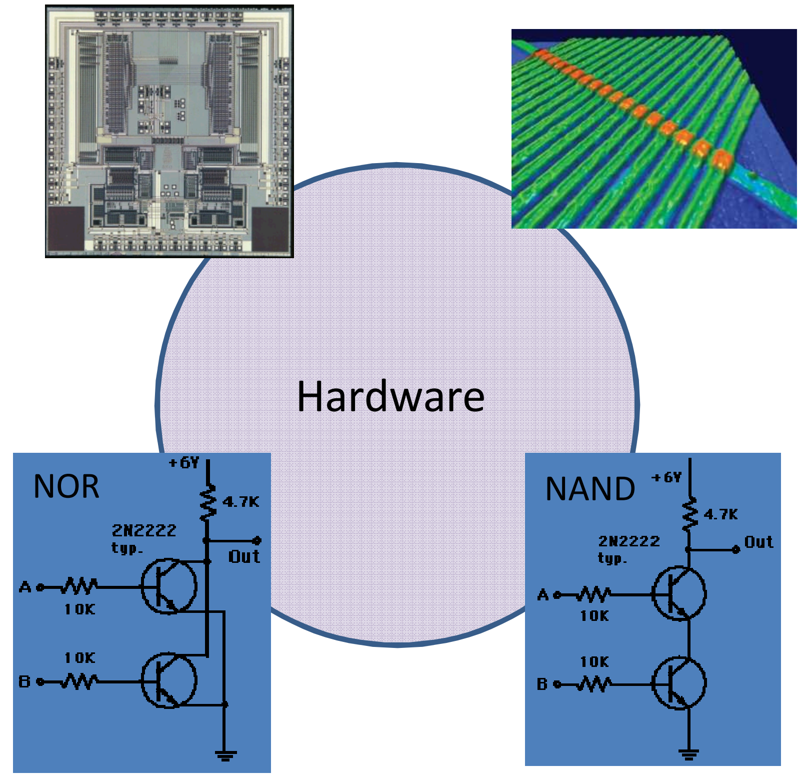




position cells, control polarization, and direct synaptic connections

# Objective 2: Implement biological computing mechanisms in hardware



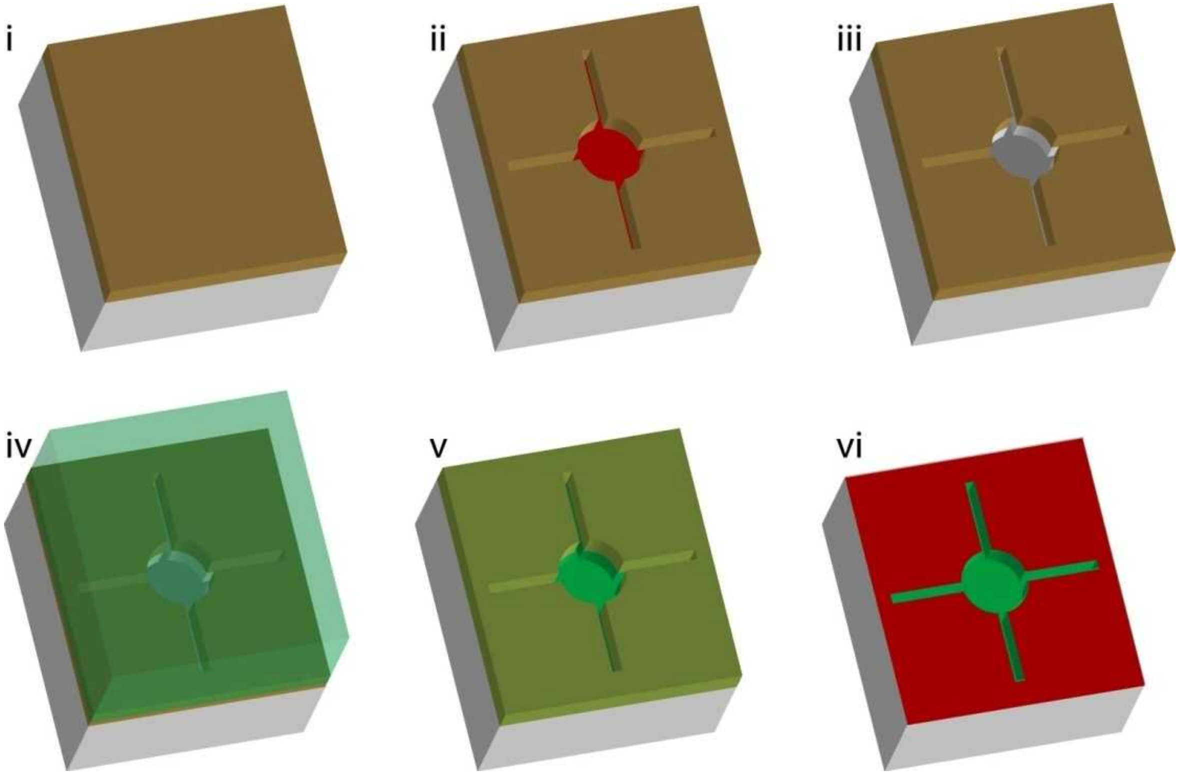

Utilize time/frequency not just for clocking, but for modifying circuit connections

# Engineering Living Neural Networks

# Topographical & chemical cues for network engineering

**Microsystems and Engineering Sciences Applications Project (MESA)**

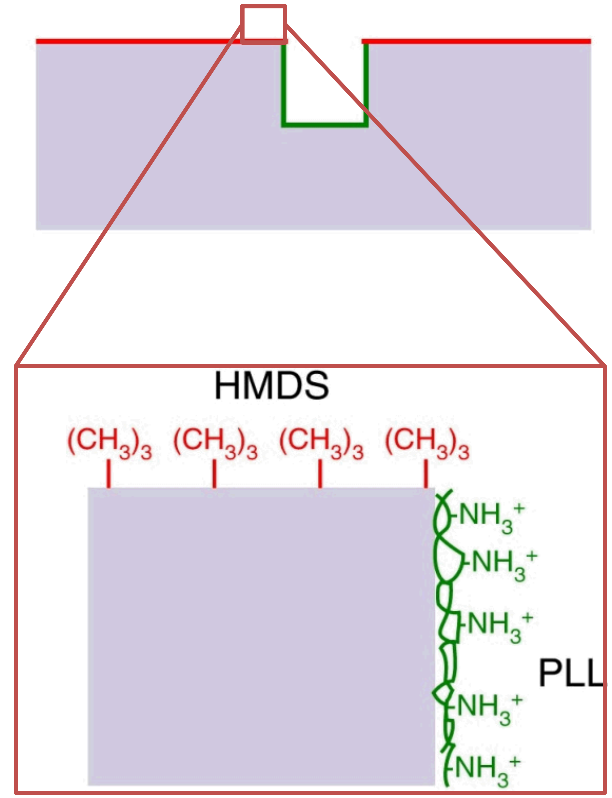
- Photolithographic techniques to create bi-functional surfaces



# Bi-functional surfaces for promoting cell adherence and repulsion

- Individual neuron guidance cues consisting of adhesive (PLL) and repellent molecules (HMDS) embedded into a glass substrate

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.




*C.D. James et al., Biomaterials 2011, in press*

# Guidance cue geometry & neuron polarization

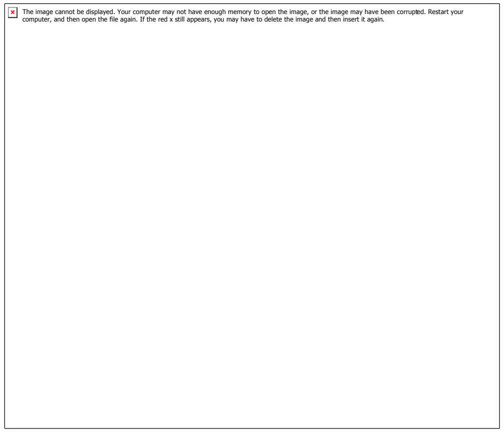
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

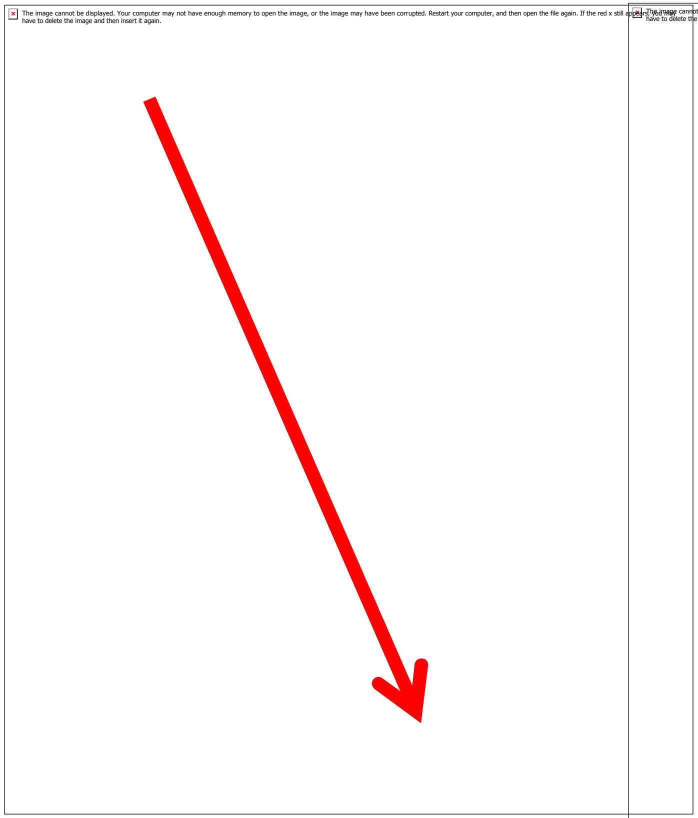
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

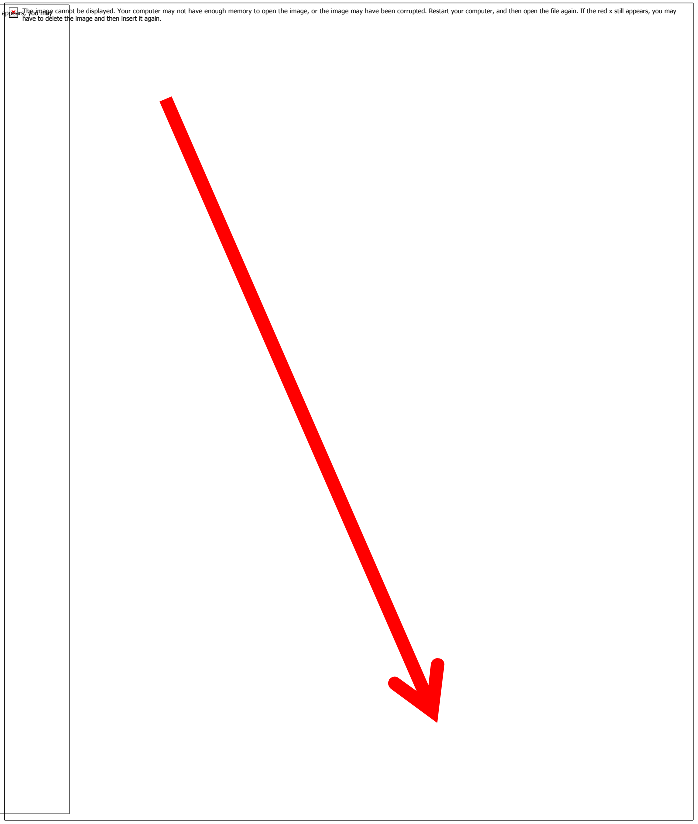
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Specific guidance of cell attachment and neurite outgrowth

Cell bodies attach to nodes (n), long neurites extend along continuous lines (c), short neurites extend along interrupted lines (i)



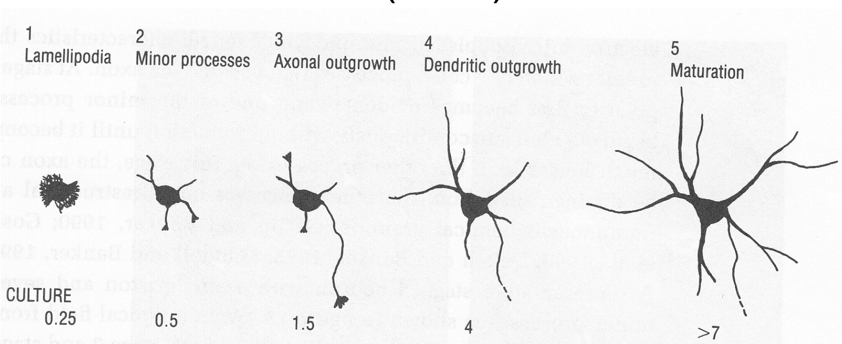

-small *g* provides no growth differential

- large *g* prevents dendrite formation

*C.D. James et al., Biomaterials 2011, in press*

# Guiding neurons to cytoarchitectural maturity

Banker and Goslin (1998):



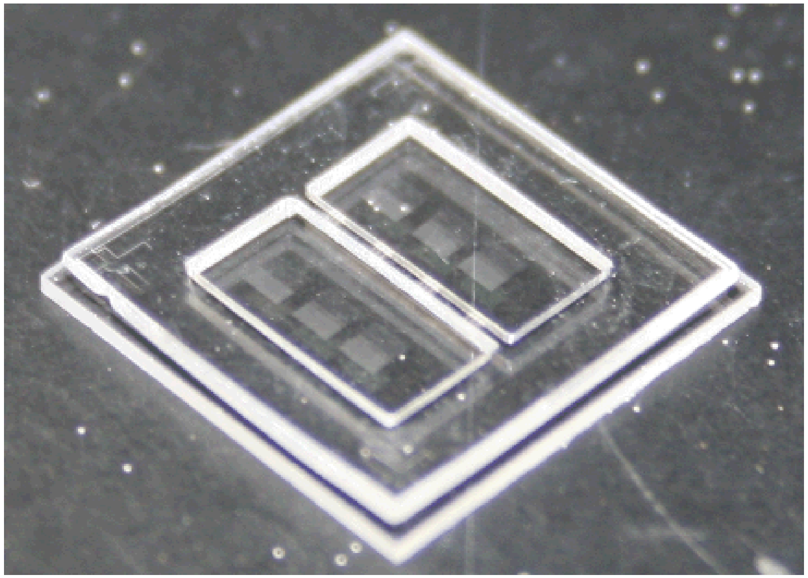


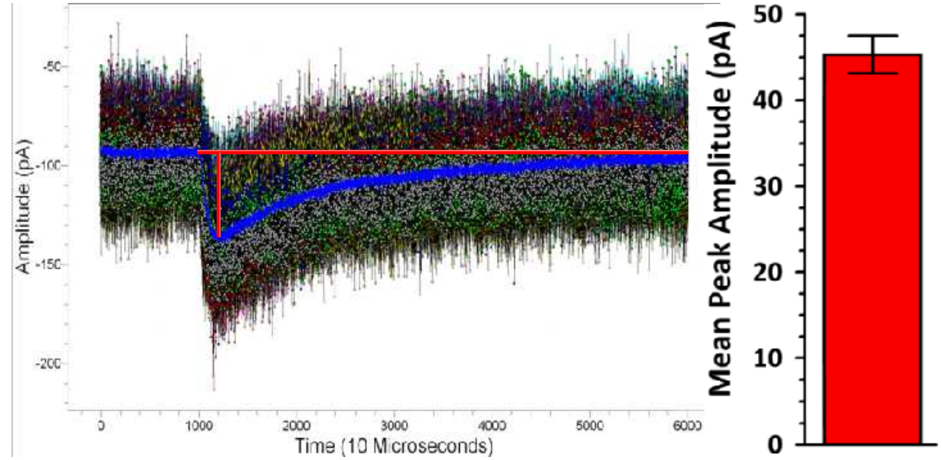

S2’



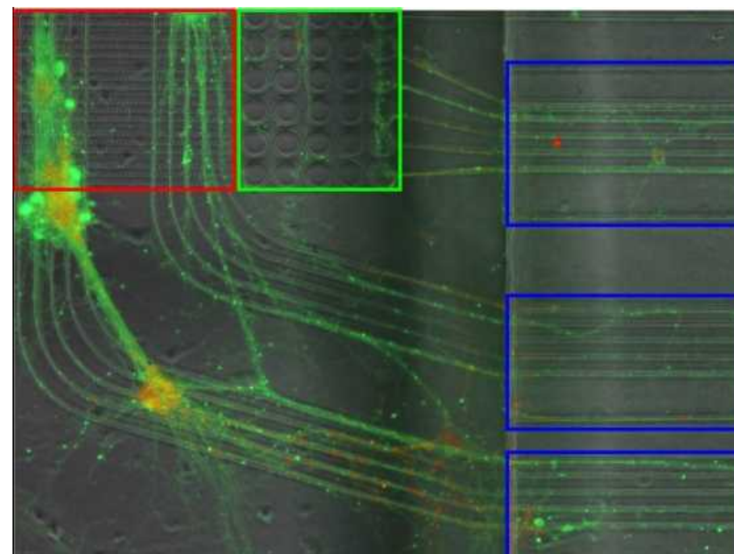
S3

# Engineered corticostriatal networks using microfluidic compartmentalization

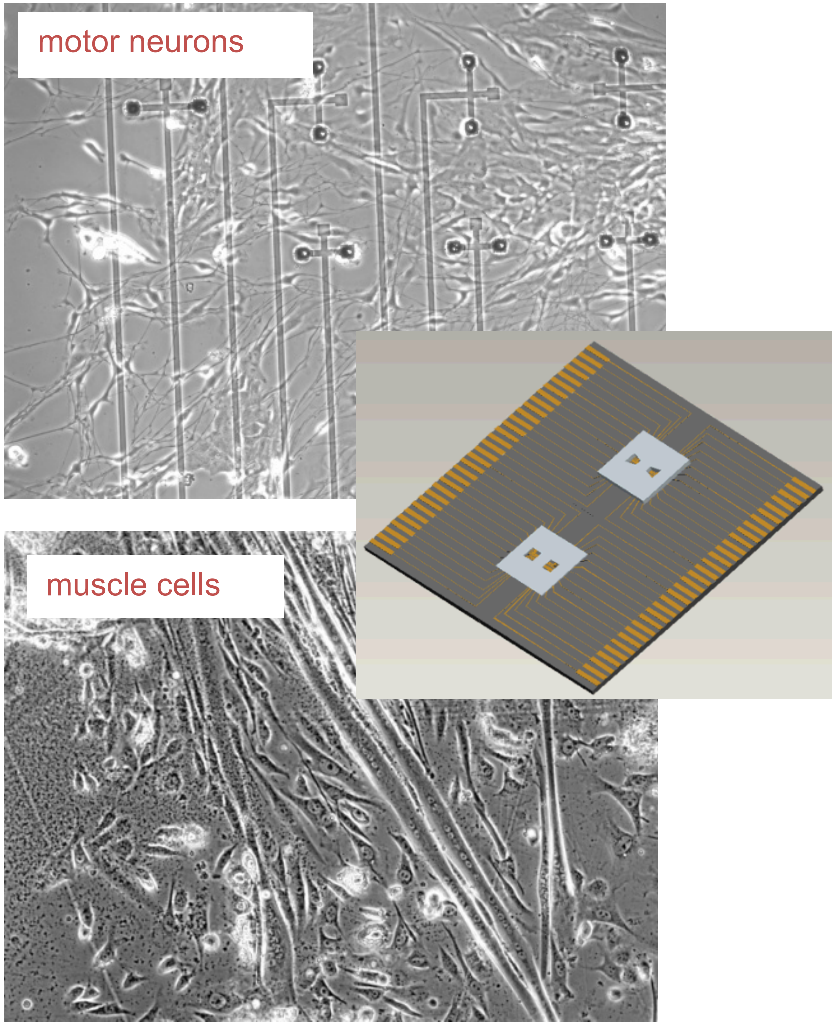


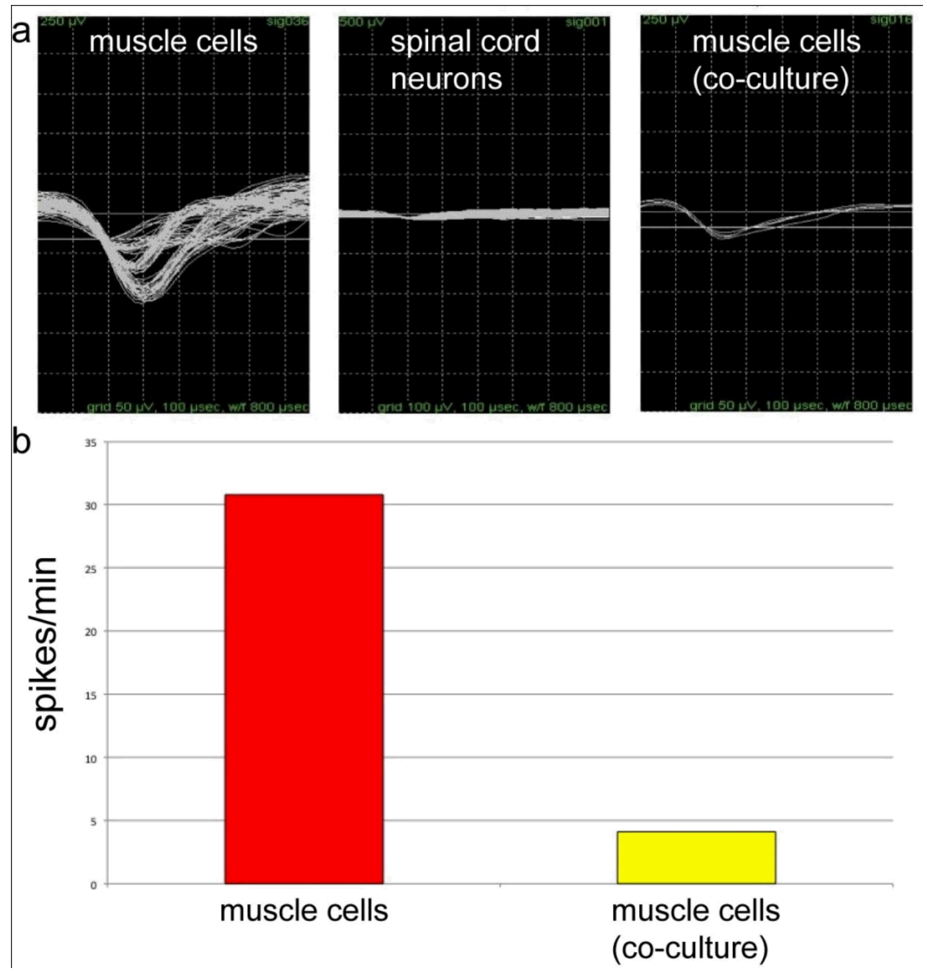



The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.



# Electrical activity in compartmentalized networks – unique behavior compared to mixed cultures




*M. Romero-Ortega, UTA*

# Programmatics & Publishing

DARPA ReFiTS: Restoring Function Through Structure Program being formulated by DARPA PM LCDR Joseph Cohn with Chris Forsythe – $275K, 2009

DTRA proposal, Topic CBM-PLAT4 – Interactions between CNS and immune system during pathogenesis; Subject to Availability of Funds FY12

Two technical advances filed, two invited talks at international conferences (St. Petersburg, Russia – 10/07; Ispra, Italy – 6/08)

Presentations: American Vacuum Society (talk) – 2009; Society for Neuroscience (poster, M. Baca) – 2009; Society for Neuroscience (poster) – 2010

Manuscript 1 – Combined chemical and topographical guidance cues for directing cytoarchitectural polarization in dissociated primary neurons – **Biomaterials (Impact Factor 6/2011= 7.88), accepted, 9/2011.**

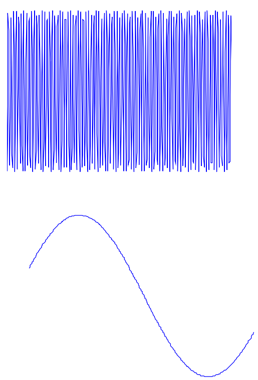
Manuscript 2 – in preparation, MEA recordings from compartmentalized NMJ networks, with UTA.

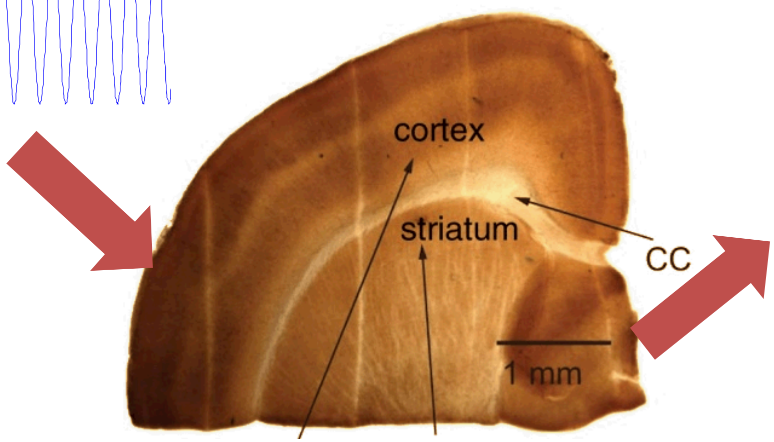
Manuscript 3 - J Neural Eng – examining data for buried microfluidic channels and engineered networks

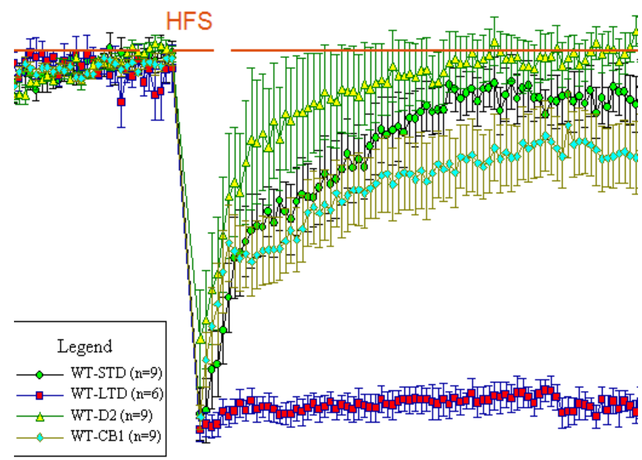
# Implementing Biological Mechanisms into Hardware

# Characterize the frequency-dependence of plasticity in CSNs

- Many biological neural networks are sensitive to stimulus frequency
- **Can such frequency-dependence be incorporated into hardware?**



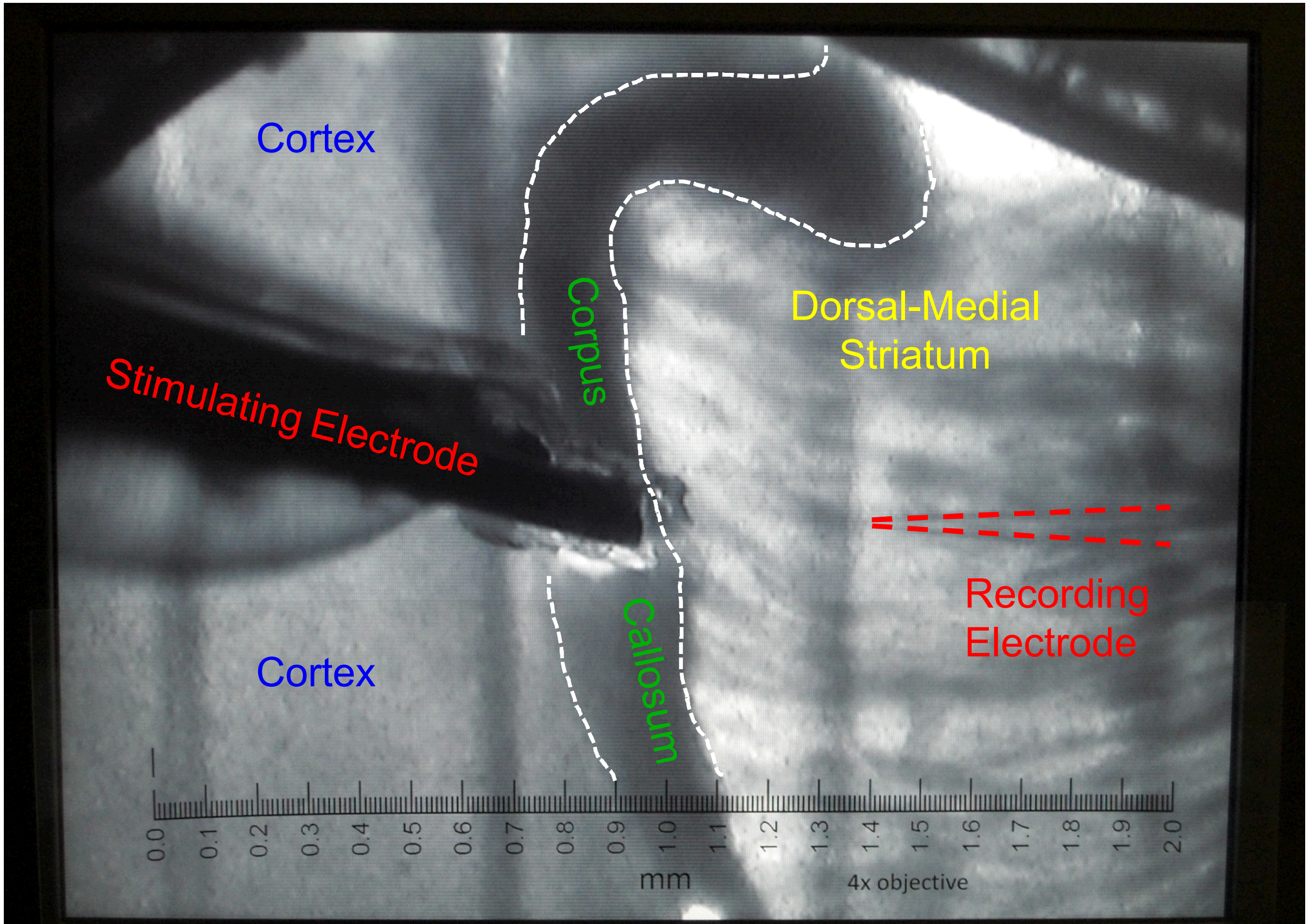



LTD, LTP

time constants, offsets

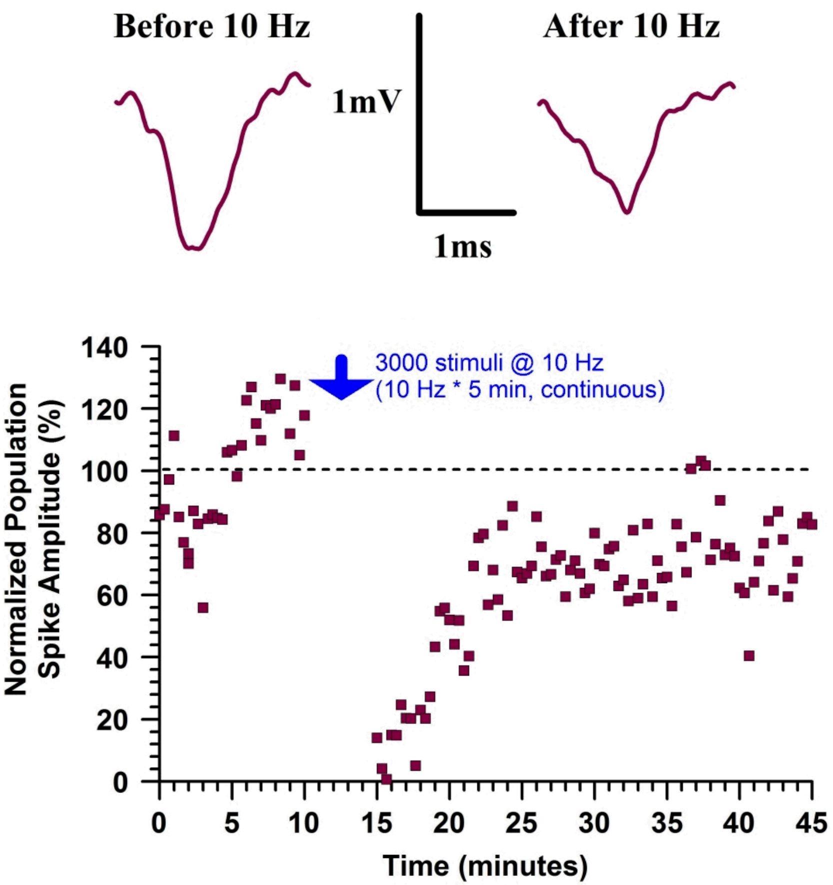
# Field recordings in the mouse dorsal-medial striatum



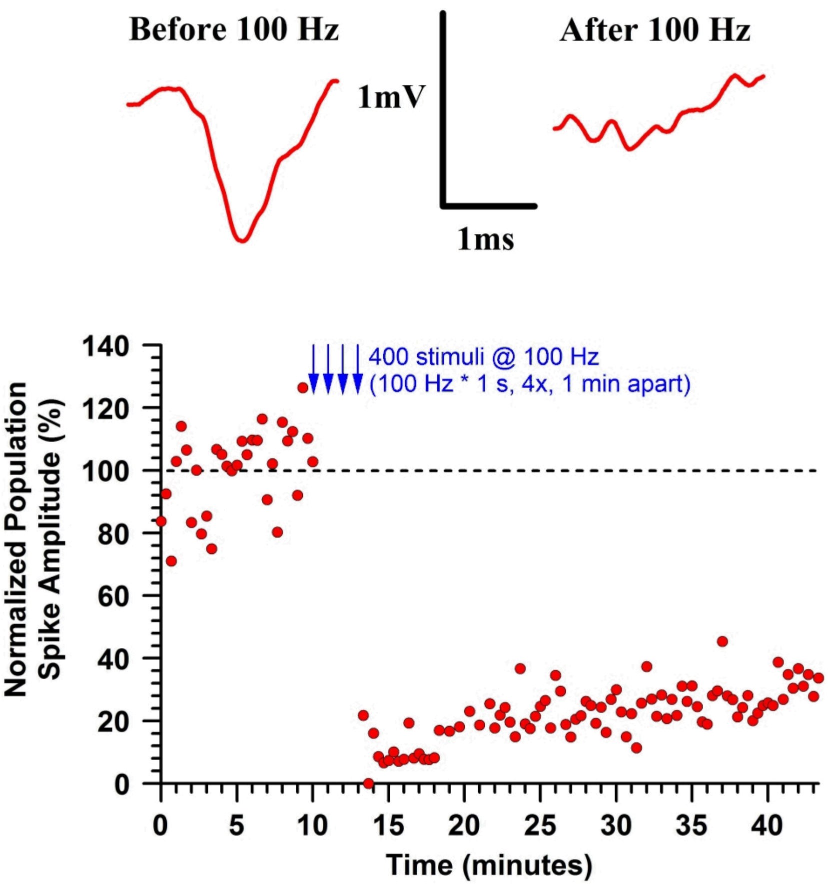

*M. Baca, A. Schiess, D. Jelinek, D. Partridge*

# Frequency response in the mouse dorsal-medial striatum

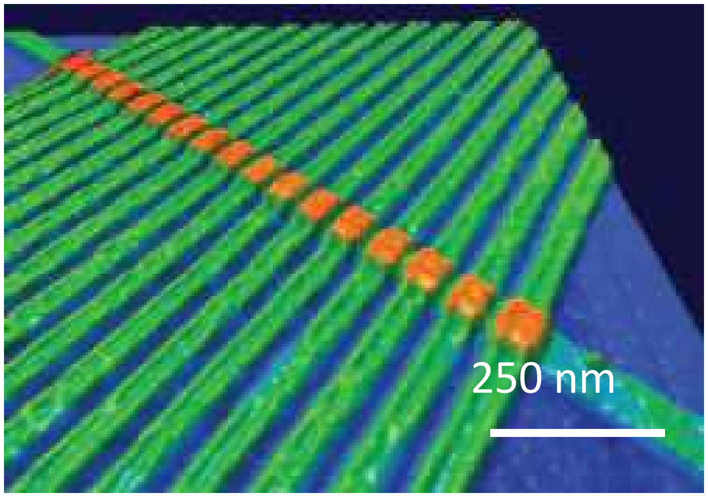
**Theta Frequency Induction: Weak LTD**

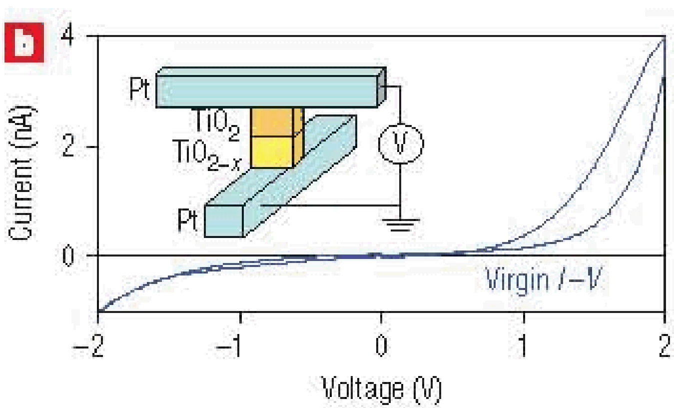



**Gamma Frequency Induction: Strong LTD**

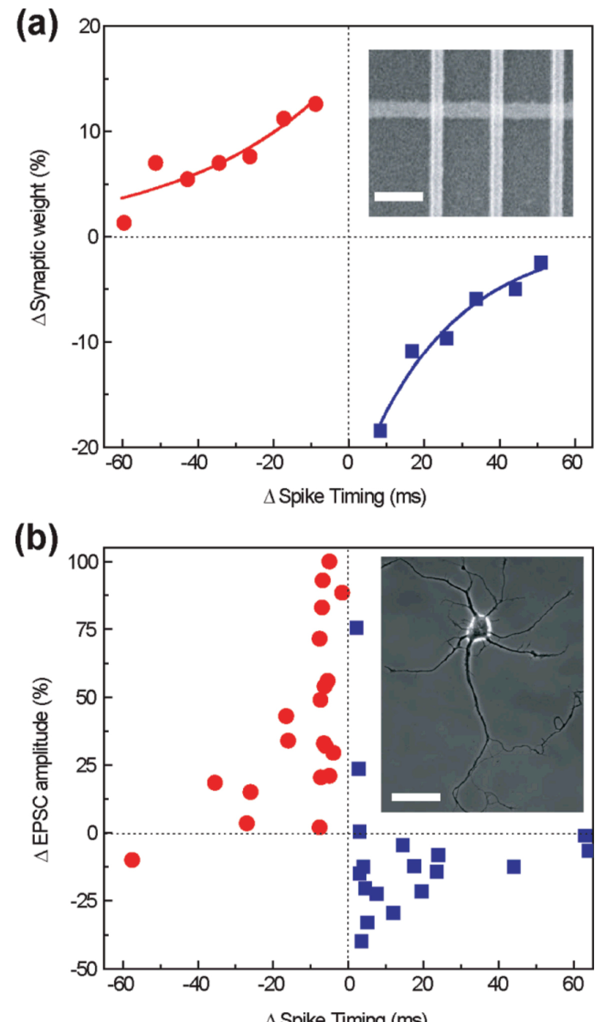


# Memristors: nanoelectronic circuit elements with synaptic properties




Strukov 2008, HP labs




Lu, U. Michigan

# Near-term plans/goals for nextgen computing work

Collaborating with SNL's Radiation-hardened CMOS department and HP for memristor device fabrication and characterization

Design and fabricate tantalum oxide memristor structures

Develop methods for modulating state changes in memristors

Fabricate a planar bismuth manganite (multiferroic) interdigitated microelectrode array – novel multistate memory material

# Team members

- Conrad James (1714) – PI
- Darren Branch (1714) – neuromorphic computing
- Adrian Schiess, Erika Cooley (1714) - electrophysiology
- Olga Spahn, Daryl Dagel (1742) – optical systems
- Michael Baca (6111) – CSN biology
- George Bachand (1132) – cell culture

Students:

- Patrick Mickel, Erika Cooley, Jamie Howell (1714)
- Devin Jelinek (UNM)

Collaborators:

Prof. Don Partridge (UNM) – electrophysiology

Matthew Marinella (1748), Hewlett Packard