NSF Workshop 2007

Brain Science at the Interface of Biological, Physical, and Mathematical Sciences, Computer Science, and Engineering: Analysis of New Opportunities

Biomimetic Computational Systems: Understanding Information Processing in the Brain

1. How does the brain encode, represent, and transform information?: What are the essential computational properties of the brain?
2. Is it possible to develop “biomimetic” neural systems that capture the essential computational properties of the brain?
3. Can biomimetic computational systems interact with the brain through real-time, bi-directional communication?

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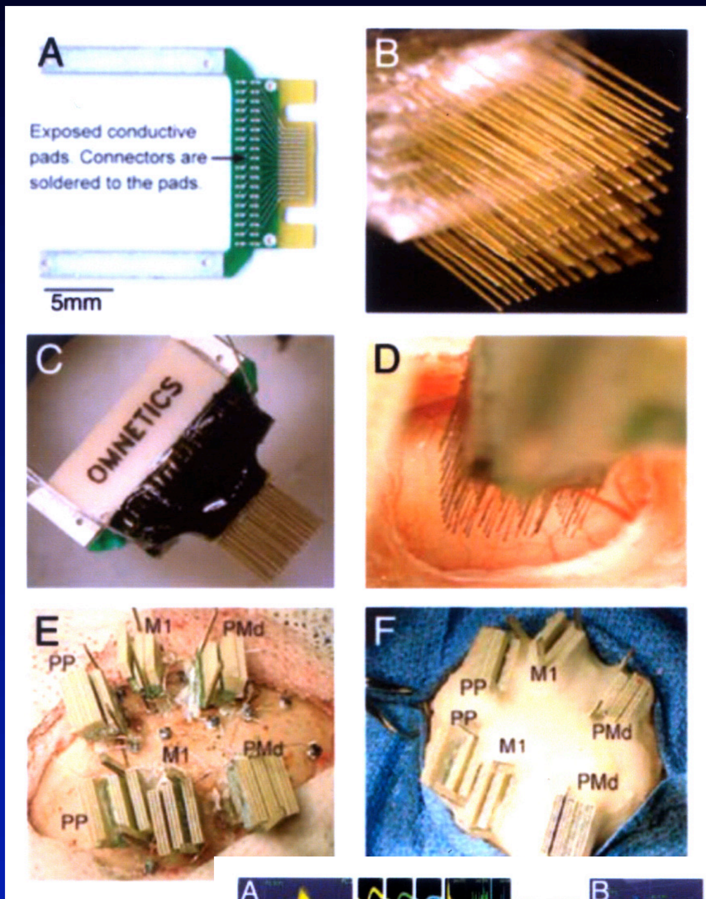
Biomimetic Computational Systems: Understanding Information Processing in the Brain

1. How does the brain encode, represent, and transform information?: What are the essential computational properties of the brain?

   - advent of multi-neuron recording / fMRI in intact, behaving animals and humans
   - opportunity to explore population dynamics of neural coding: spatio-temporal coding
   - what information can be coded in the spatio-temporal capacity of populations of neurons? – given variability among neurons
   - how does that capacity depend on underlying cellular/molecular mechanisms?
   - how is information transformed as it propagates through the nervous system?
   - how do these transformations map onto "cognitive functions" – higher thought processes?
   - advantages to biological coding yet to be discovered?

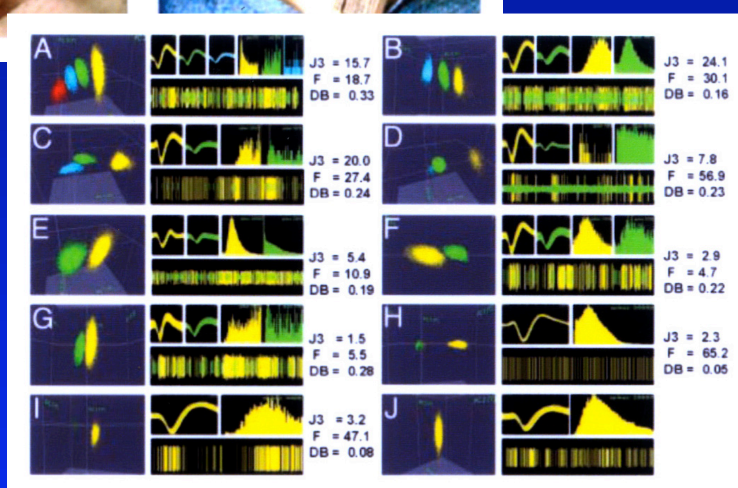


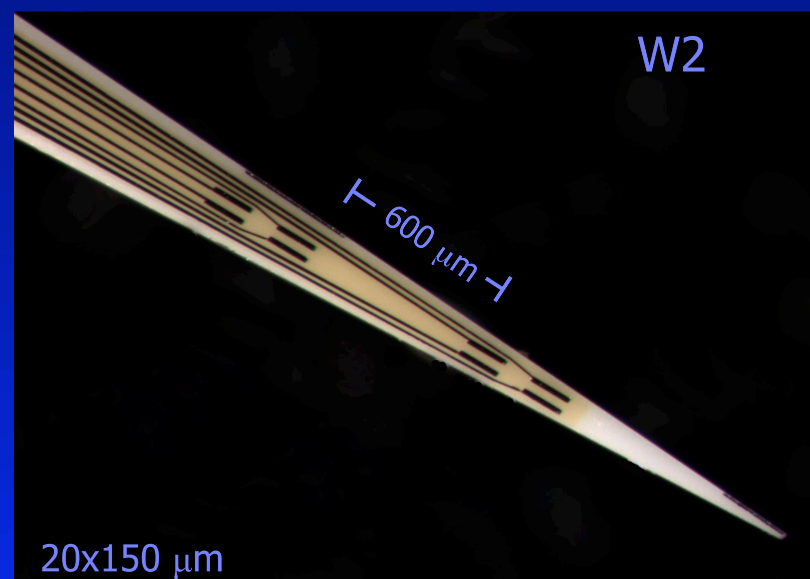
Multi-Site Recording Array Technologies

- microwire arrays; multiple arrays
- silicon-based micro-fabricated electrodes
- ceramic-based micro-fabricated electrodes; chemical sensors
- <u>need to push the envelope of multi-site recording array technology</u>

Nicolelis
Duke Univ.

Chapin
SUNY
Downstate

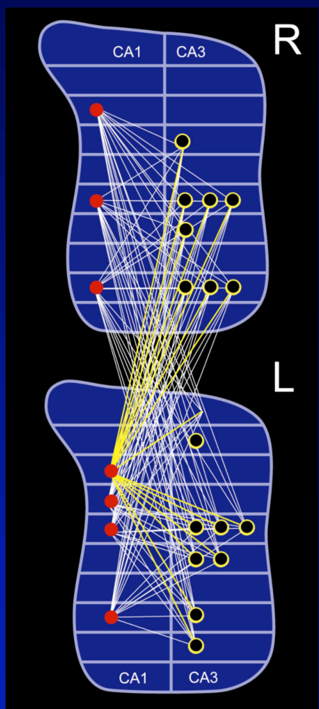


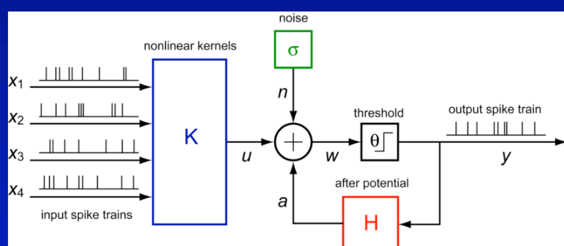


Gerhardt – Univ. of Kentucky

Advanced Algorithms for Decoding Brain Computations

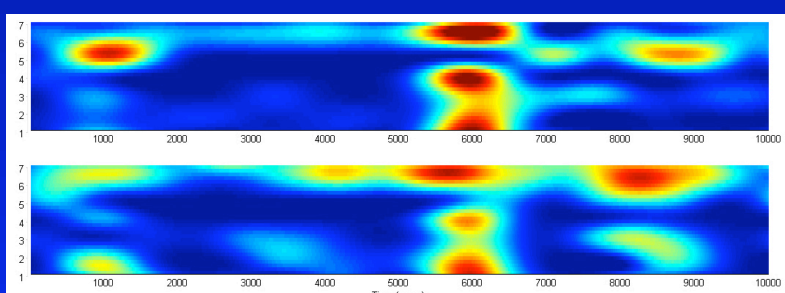
- population vector
- optimal linear est.
- linear dynamic models
- nonlinear dynamic models
- adaptive models



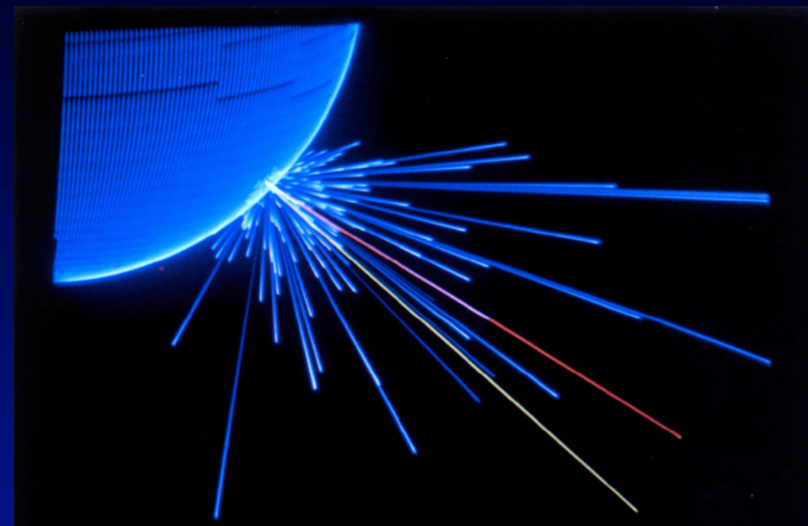


Predicted Pattern

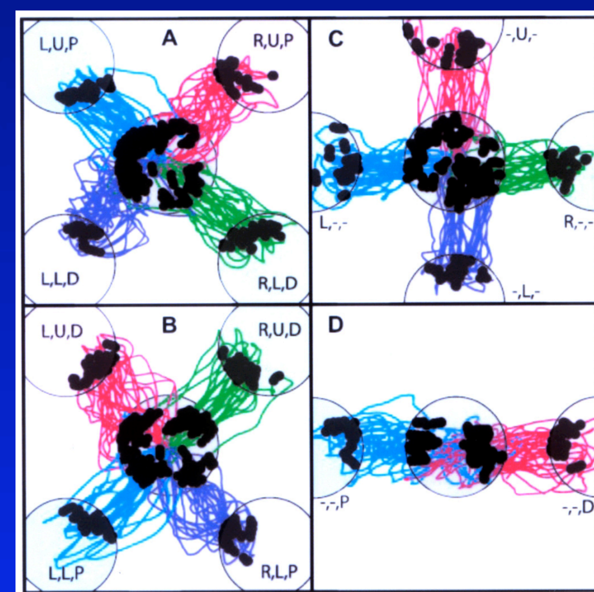
Recorded Pattern



Song, Berger – USC

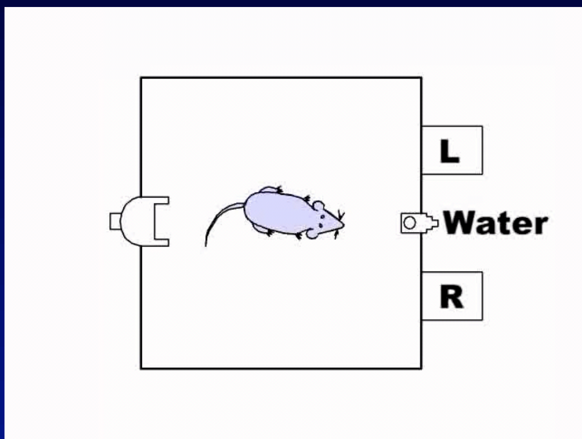


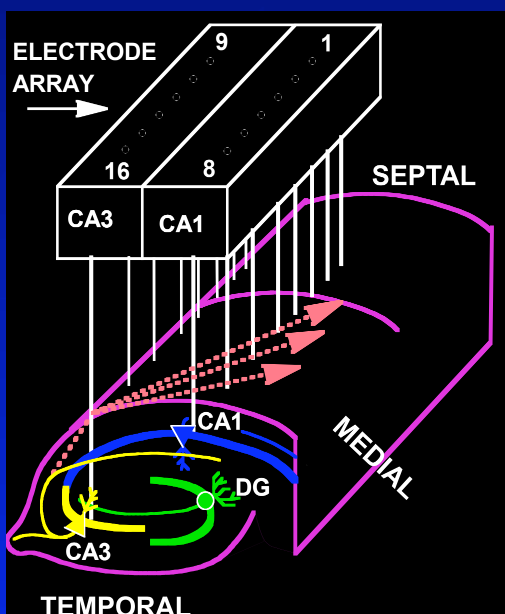
Georgopolous – Univ. of Minnesota



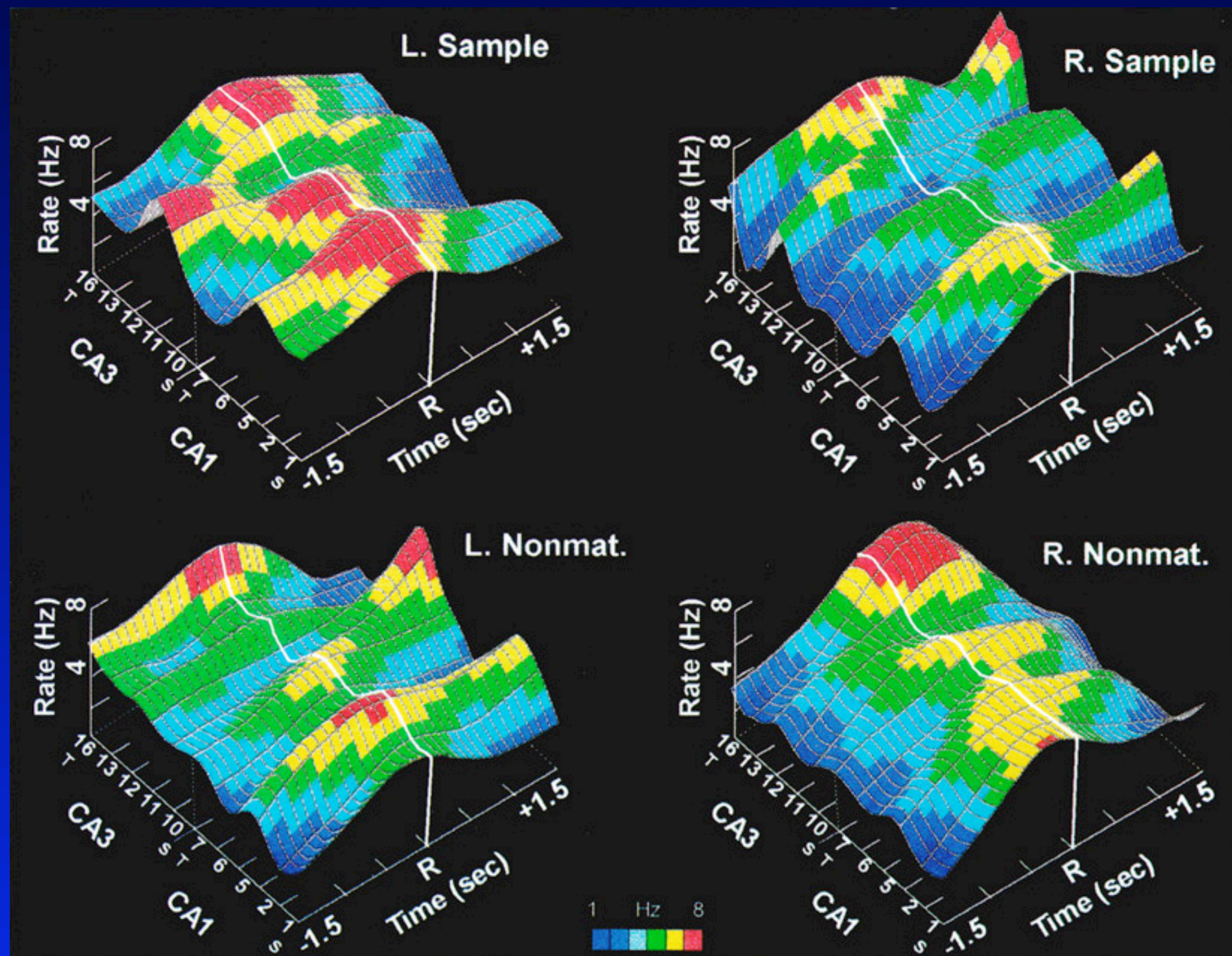
Schwartz – Univ. of Pittsburgh

Electrophysiological Indices of Cognitive States and Operations





Delayed Non-Match-to-Sample Memory Task



Deadwyler – Wake Forest Univ.
Eichenbaum – Boston Univ.

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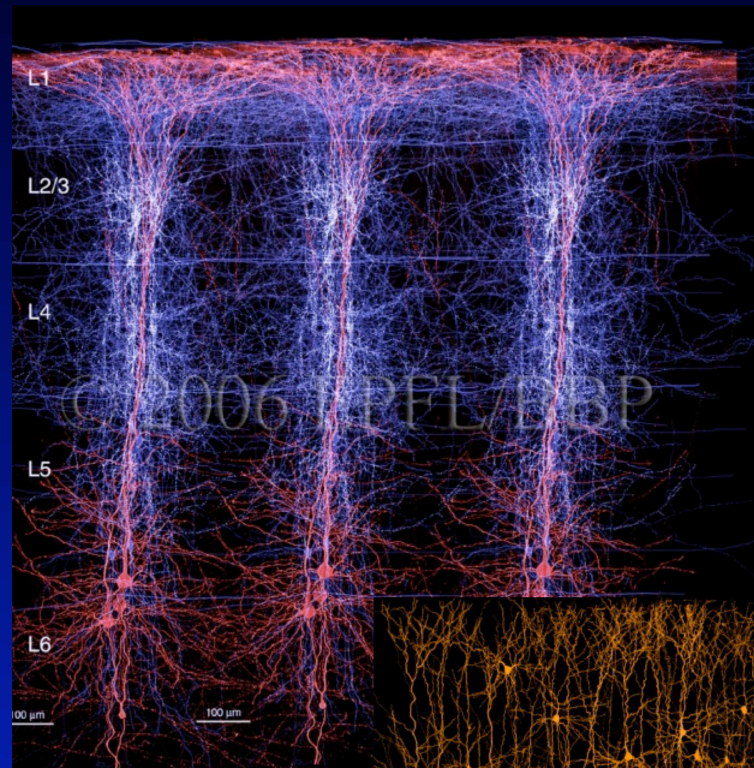
Biomimetic Computational Systems: Understanding Information Processing in the Brain

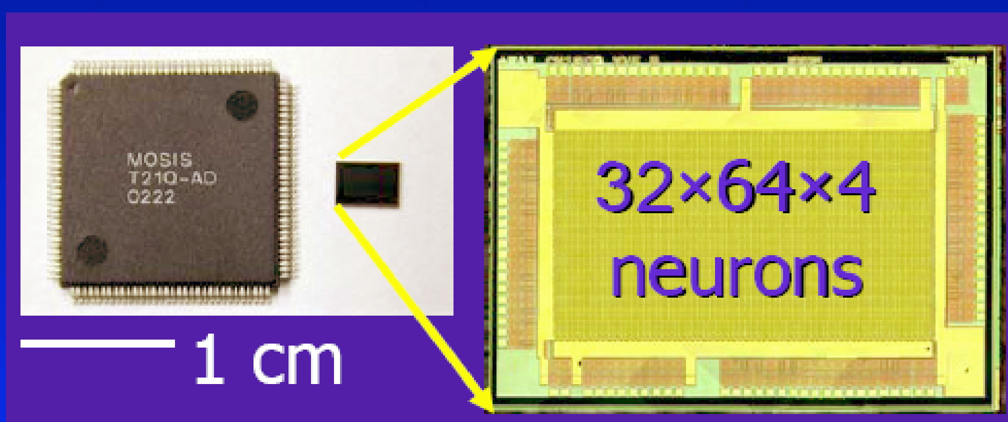
2. Is it possible to develop “biomimetic” neural systems that capture the essential computational properties of the brain?

- increased fundamental anatomical, physiological, etc., knowledge of neural systems; increased computing power and computational hardware
- should be able to start building systems that really act like biological systems – computational, robotic, "cognitive" systems, etc.
- neuronal processes are strongly nonlinear: what types and orders of nonlinearity need to be considered?; nonstationarities (learn./develop.)
- what does it take to put together “mini-systems” of a cortical column?, a hippocampal slice?, a cerebellar folia? a retina?
- what types of hardware representations of such neural systems can be realized?
- can we develop hardware platforms that are both large-scale and flexible to use as investigational tools?

Experimentally-Based, Biomimetic Models of Neural Systems

- "Blue Brain" Project (H. Markram, EPFL, Switzerland) – experimentally-based, functional, structural, biochemical model of a neocortical column – simulation of a 10,000 neuron system using an IBM multi-processor "Blue-Gene" computing system
- "Neurogrid" Project (K. Boahen, Stanford Univ.): emulating millions of visual cortical neurons using multi-processor arrays; programmable, hybrid, analog-digital circuitry

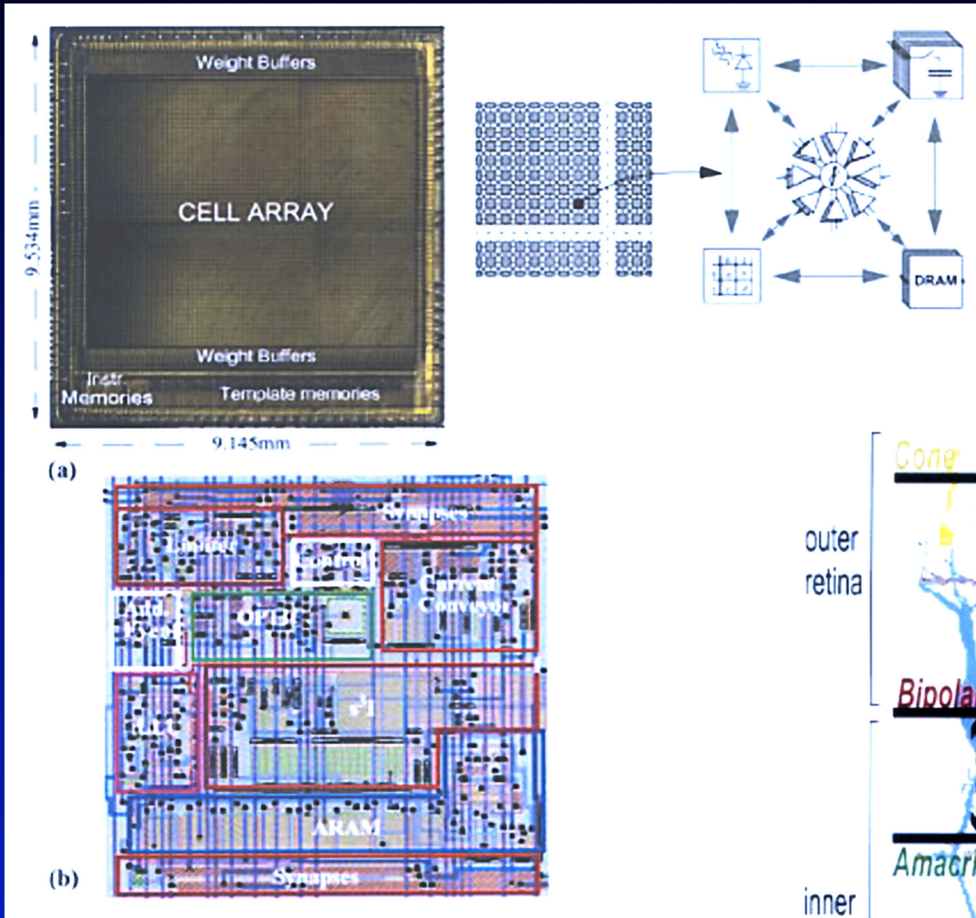


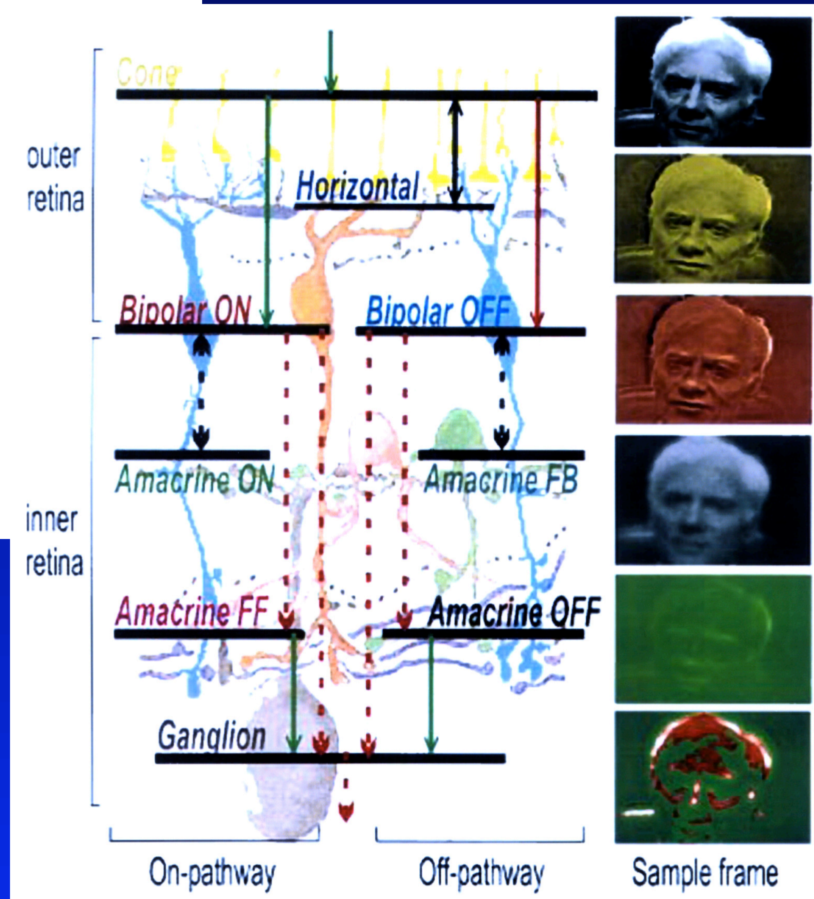


Boahen – Stanford Univ.

Markram – EPFL, Switzerland

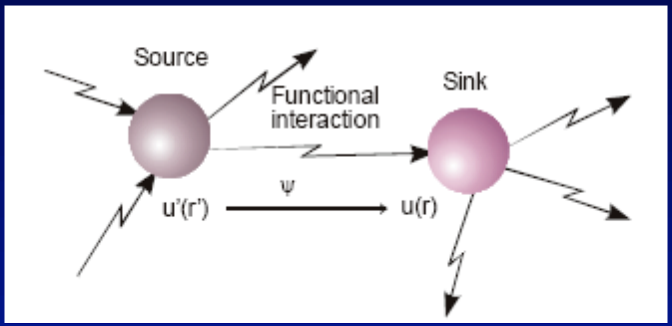
Biomimetic Neural Systems that Capture the Essential Computational Properties of the Brain





Cellular Neural Network (CNN) implementation of a biologically-based, multi-layer model of the retina – Werblin, UC Berkeley; Roska, Hungarian Academy of Sciences

Multi-Level, Hierarchical Models of the Nervous System: Relating Molecules to Synapses to Neurons to Networks



$$(a)\quad \frac{\partial\psi}{\partial t}(r_0,t_0) = \nabla_r[D^r\nabla_r\psi(r_0,t_0)] + \int_{D_r(r_0)} \rho_p(r)\psi(r,t)$$

$$\int_{D_s(r,r_0)} P_r(r_0,t_0,r,t)\pi_g(s,r;\ r_0)\sigma(s,t)\,ds\,dr$$

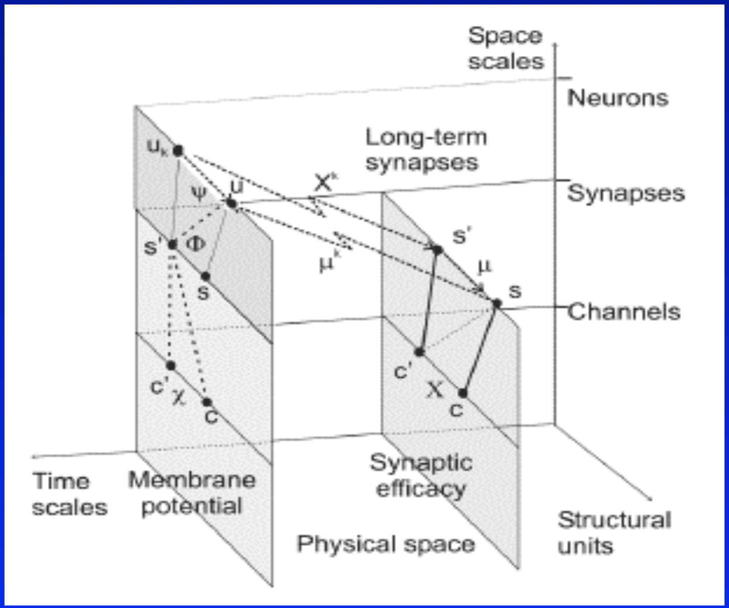
$$+\ \Gamma_r[\psi(r_0,t_0);\ \psi_{refr}]$$

$$(b)\quad \frac{\partial\mu}{\partial t}(s,t) = \nabla_s[D^s\nabla_s\mu(s,t)] + \int_{D_r(r_0)} \rho_p(r') \int_{D_s(r,r_0)}$$

$$P_s(s,s')\pi_g(s',r';\ r_0)\mu_0(s',t')\,ds'dr' + \Gamma_s[\mu(s,t)] \quad (4)$$

Chauvet – Univ. of Angers, France

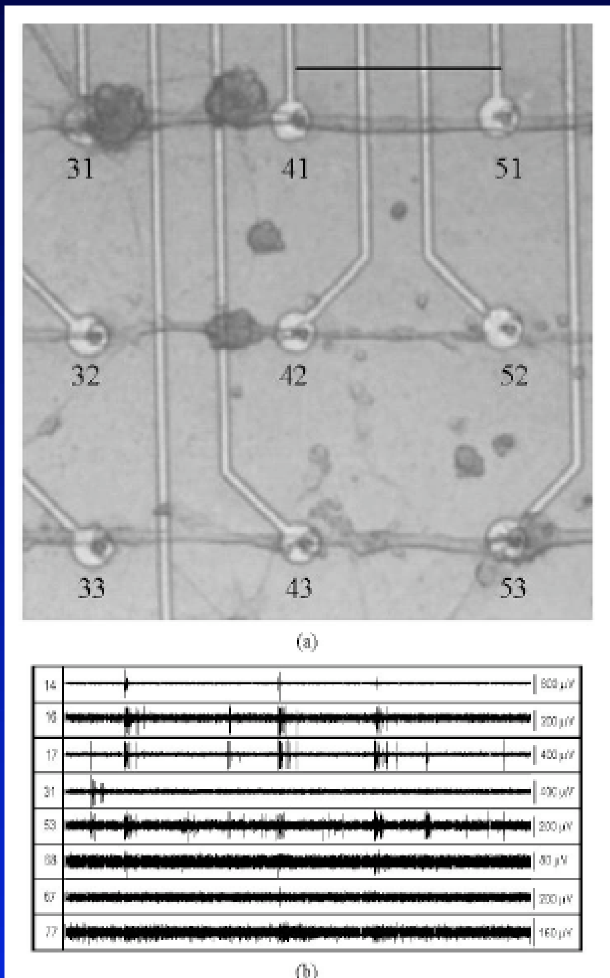
- need for a comprehensive theoretical framework that can account for molecular, cellular, system, and multi-system function
- capable of taking into account multiple time and space scales of the nervous system
- capable of relating changes at one level of the neuronal hierarchy to changes at other levels
- e.g., n-level field theory of Chauvet; also see J. Cowan



Biomimetic Computational Systems: Understanding Information Processing in the Brain

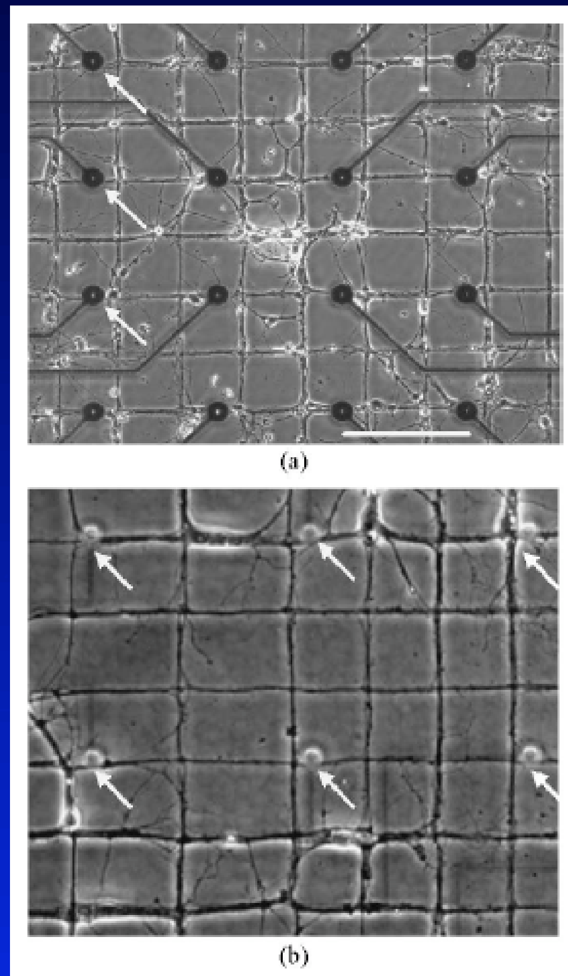
3. Can biomimetic computational systems interact with the brain through real-time, bi-directional communication?
   - advanced tissue culture “designer circuit” methods: neuron-silicon “co-interrogation” of reduced neural systems
   - biomimetic system-neural system “co-processing of information” in the brain: can we detect fundamental brain operations such as object recognition or memory formation?
   - can we develop biomimetic systems that assist or enhance fundamental brain operations
   - can we develop biomimetic systems that replace damaged brain regions – implantable neural prostheses
   - can we develop biomimetic systems that actively “query” the brain as to its “state” or its current “computational operation” – hybrid systems that “learn how the brain works”

Surface Chemical Patterning to Create “Designer” Neural Circuits that Interface Predictably with Silicon-Based Multi-Site Electrode Arrays



(a)

(b)

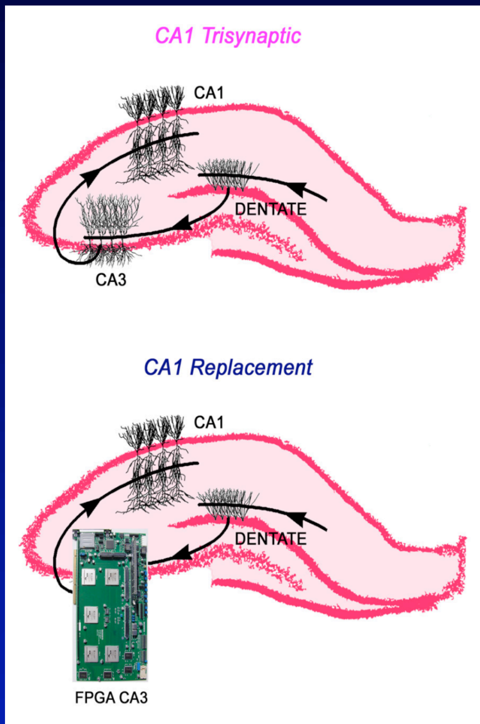

(a)

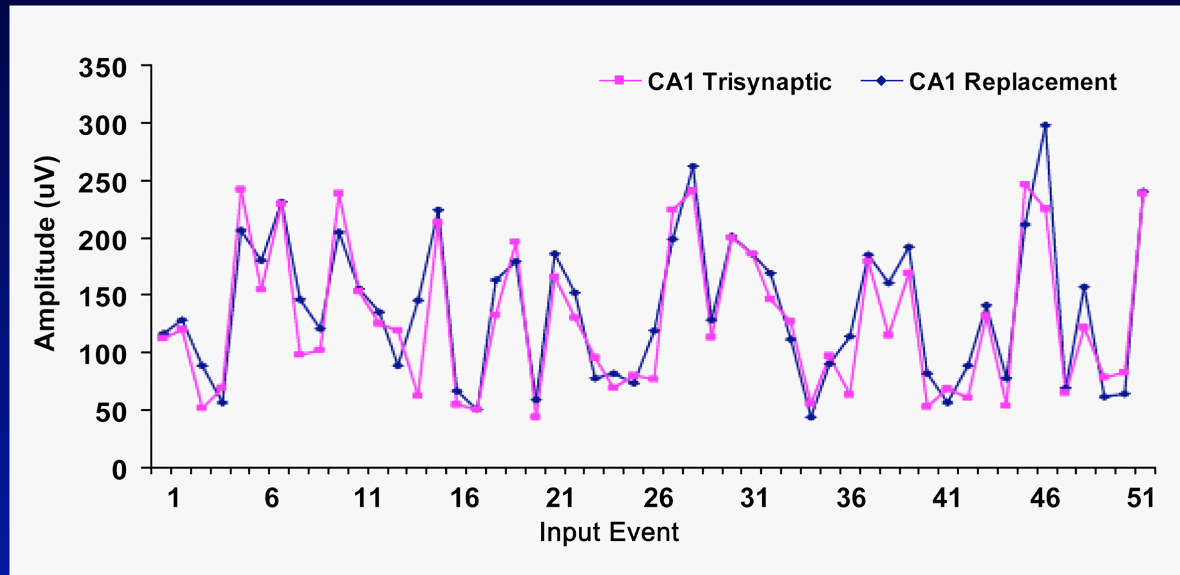
(b)

- surface chemical patterning to attract and adhere cultured neurons to “nodes” in a sensor grid
- physical and molecular constraints to shape “directionality” of circuit structure and function
- combined recording-stimulation protocols to understand computational properties of reduced neural circuits
- possibility of controlling progressively greater complexity of neural circuits and systems

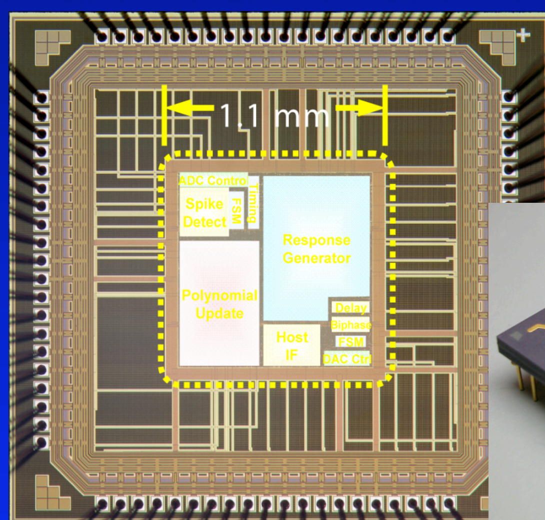
Wheeler – Univ. of Illinois, Urbana-Champaign
J. Hickman – Univ. Central Florida

Restoring Hippocampal Nonlinear Dynamics After Replacing CA3 with a Biomimetic, Hardware Model





- *experimental measurement of the nonlinear properties if the dentate-CA3-CA1 circuit in a hippocampal slice*
- *nonlinear dynamic model of the CA3 hippocampal region*
- *experimental removal of the CA3 region in the slice*
- *substitution of CA3 with a hardware model restores circuit nonlinearities*



Berger et al. – USC