Interactive Neuronal and Nanoelectronic/photonic circuits

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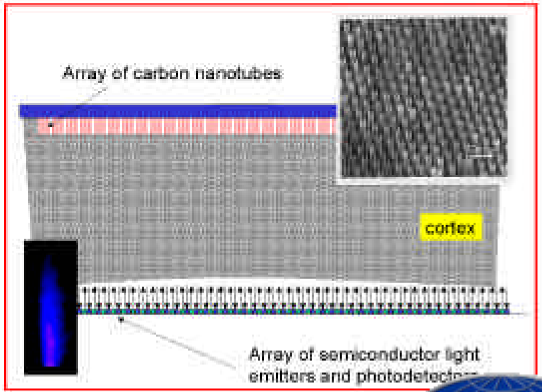
Goals:

(1) Aim at discovery and implementation of new computational paradigms acquired from interaction of a biological processor (brain) and man-made nanoscale device arrays, with emphasis on collective phenomena.

(2) Develop next generation of interactive, "smart" nanoprobe-based sensor array technology with ultra- high spatio/temporal resolution for a broad range of neuroscience imaging applications.

(3) Develop new theoretical approaches that bridge neuroscience and computer engineering, with emphasis on spatially distributed computing



Computing/Information Processing Technology ca. 2030?

If "invent by increment" :

Today's digital microelectronic computer: (Si-based, 0.18 μm)
basic hardware architecture "locked-in"

↓

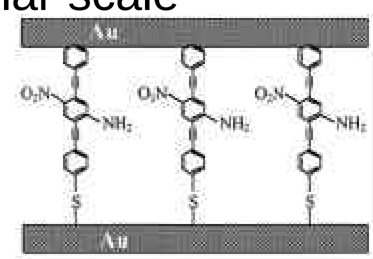
Moore's law (ca. 2020)?:
limits to microprocessor size/speed

→ device size (CMOS)
→ interconnects
→ packaging & dissipation

↓ ?

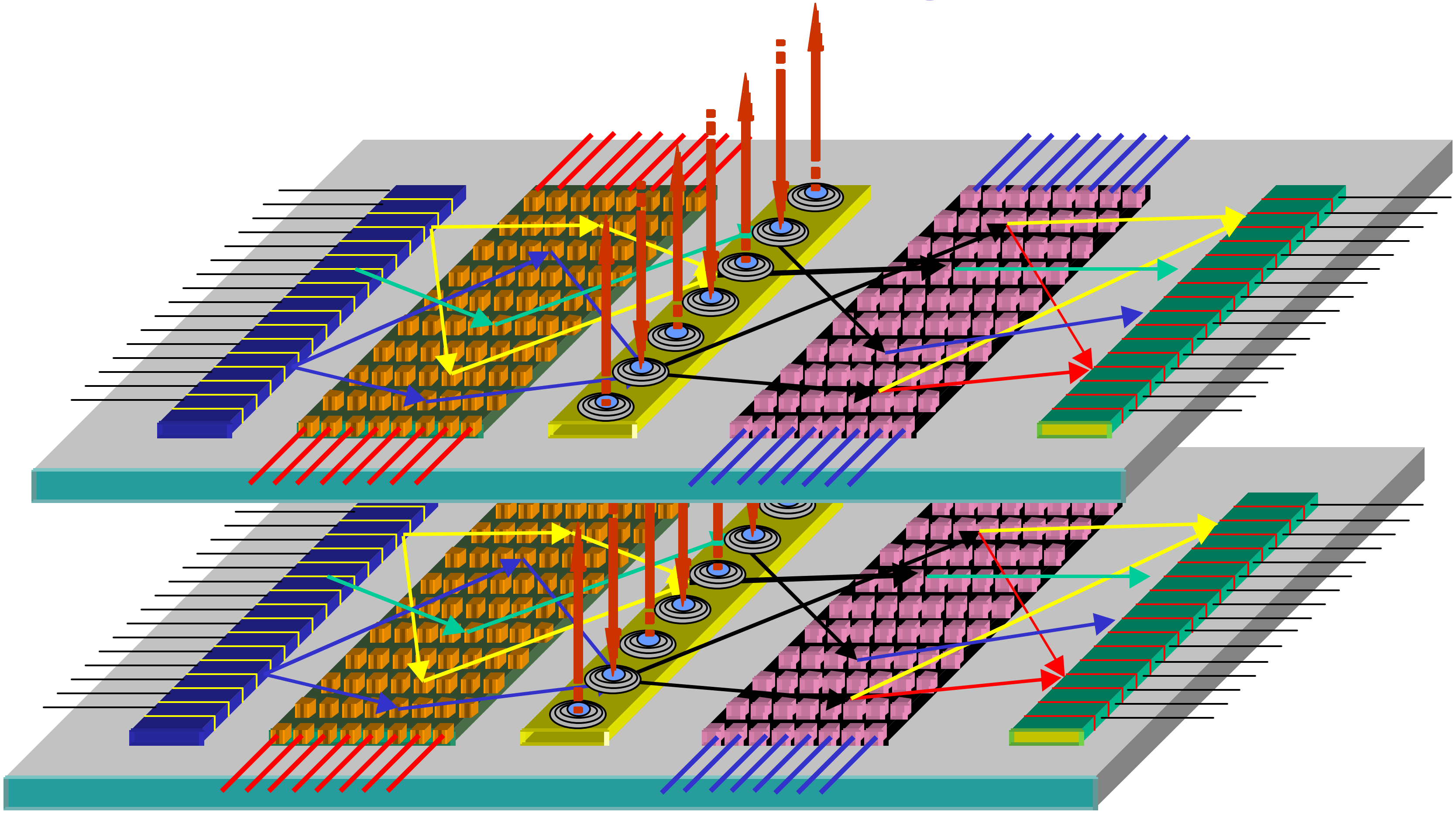
Molecular electronics (self assembly)

→ conductors (DNA wire?)
→ switches, active devices on molecular scale



Photonic superchip?

Photonic Superchip: Ultrafast Signal Router/Processor

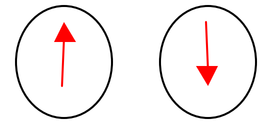


- aim for ultrafast all-optical packet and binary switching
- aim for wide wavelength range on chip-performance
- aim for large arrays >1000x1000

Future Computing Paradigms ?

Two examples:

- Quantum computing: spin 1/2 system

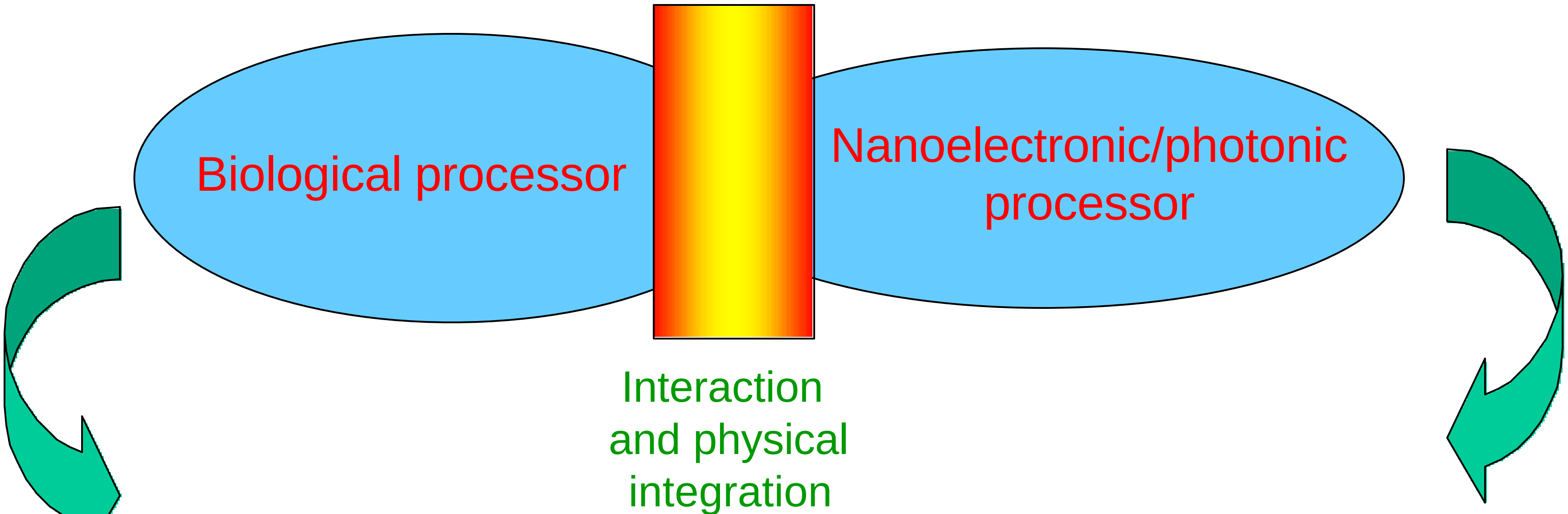


coherent superposition (phase)
entanglement (many spins) → quantum parallellism

- Spatially distributed (global) information processing

→ internet and optical networks/communication

“our paradigm”:

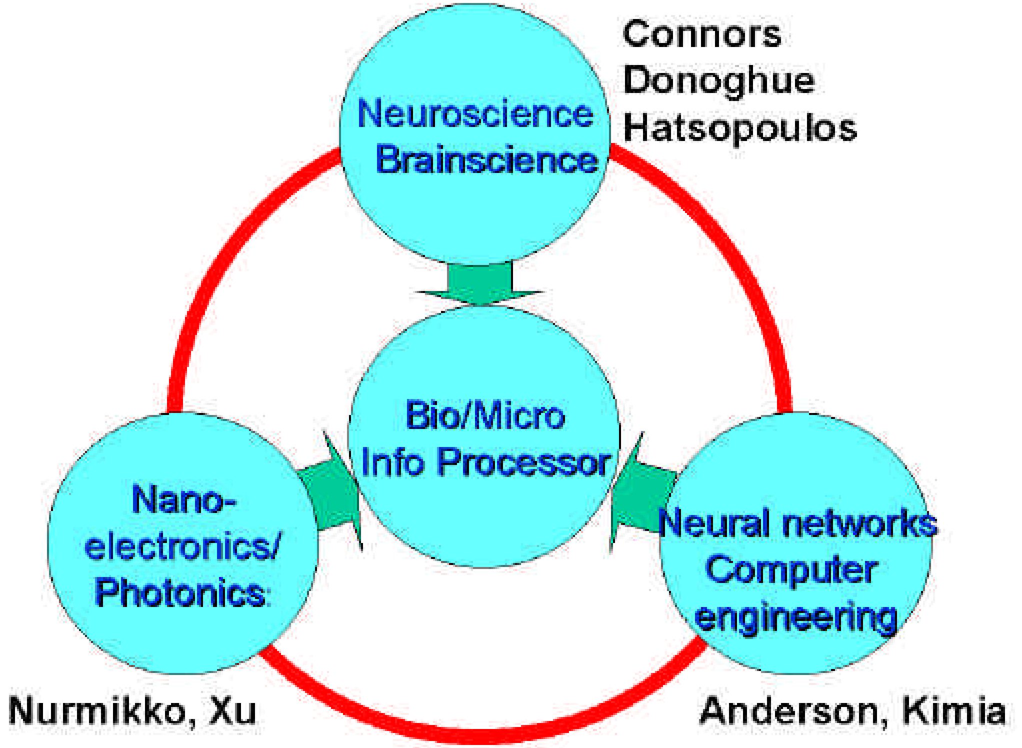


Neural network (e.g. brain) as a massively parallel, spatially distributed analog computer

Nanoscience/nanotechnology: large-scale non-silicon based interactive, monolithic transducer/receiver arrays

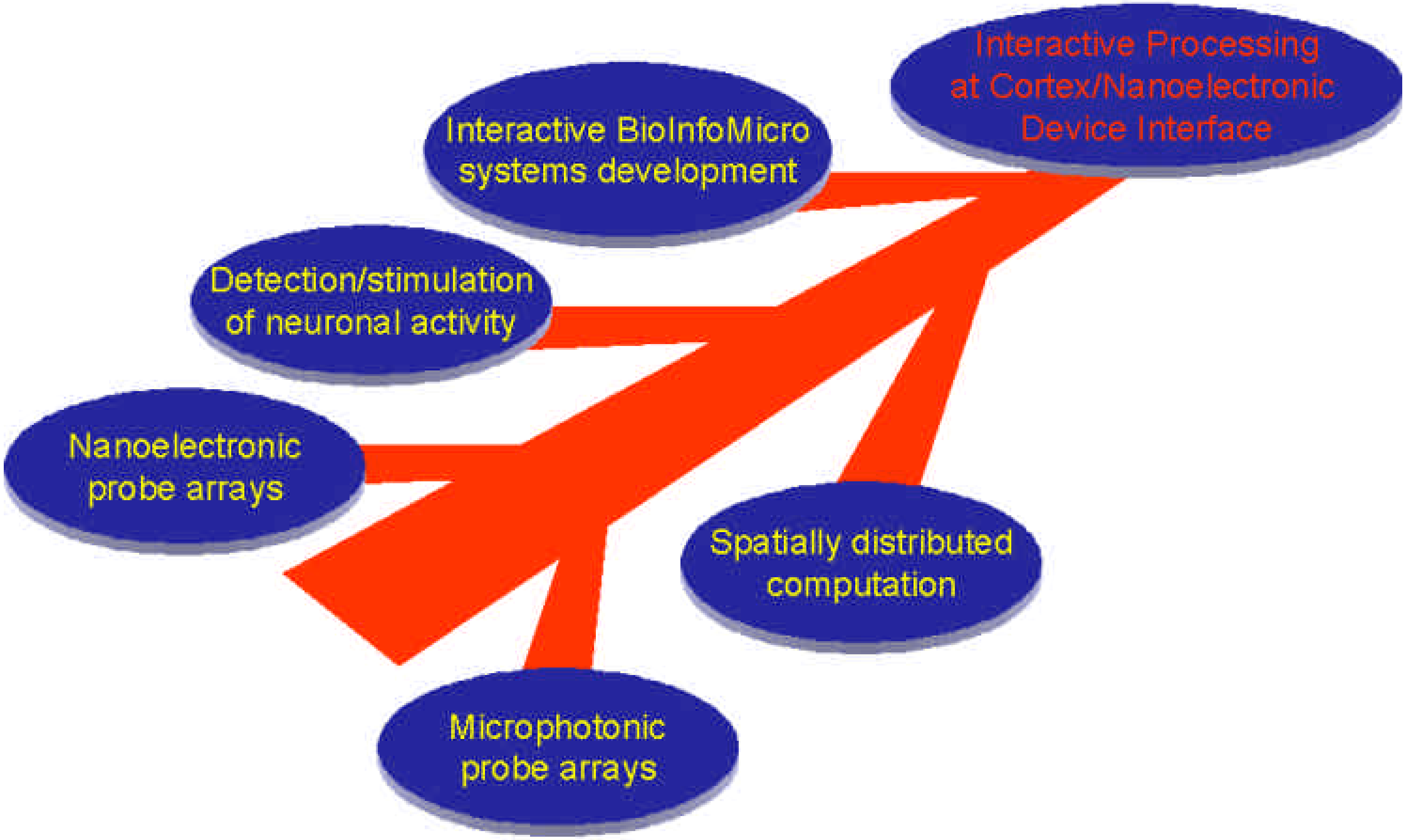
Develop massively parallel interfaces for (i) studying neuronal connectivity and spatial organization; (ii) mapping that information onto nanoelectronic/photonic chips for study of collective features to look for new computational functions

Brown Bio/Info/Micro Interdisciplinary Team:



- 6 faculty, 2-3 senior staff, 10-12 Ph.D. students (joint advising)
- Institute for Brain Science, Laboratory of Engineering and Man Made Systems, Center for Advanced Materials Research
- Central Research Facilities

Technical Structure and Task Organization of Program:



Target Milestones

Year 1:

- Demonstration of electrical recording from cortex slices by carbon nanotube electrodes
- Real time imaging of cortex slices by fluorescence optical probes based on compact semiconductor micro-optical light emitters/detectors
- Development of signal acquisition and information processing strategies for the manmade arrays

Year 2:

- Fabrication of carbon nanotube arrays and initial studies of synaptic correlations with these novel nanoprobes
- Fabrication of high density arrays of blue/green/UV LEDs and photodiodes and development of prototype high spatiotemporal resolution imaging of cortical activity
- Studies of neuronal activity by the nanoelectronic/microphotonic arrays
- Development of information theories of spatially distributed computing

Year 3:

- Demonstration of carbon nanotube arrays as spatially distributed, interactive sensors/transducers of cerebral cortex; proof of concept experiments in spatially distributed computation.
- Demonstration of microphotonic arrays as spatially distributed, interactive sensors/transducers of cerebral cortex; proof of concept experiments in spatially distributed computation.
- Connecting the theory concepts of spatially distributed computing with initial input from experiments

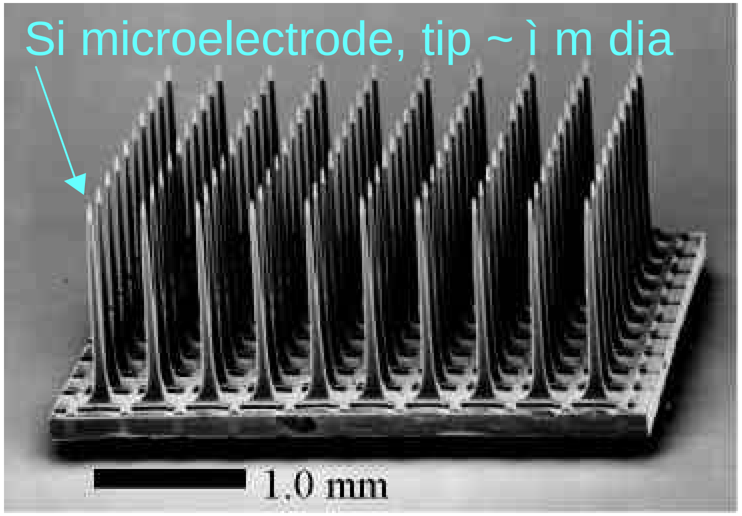
Year 4:

- Integration of nanoelectronic and microphotonic sensor/transducer arrays
- Incorporation of results from theoretical models to guide the experimental system design

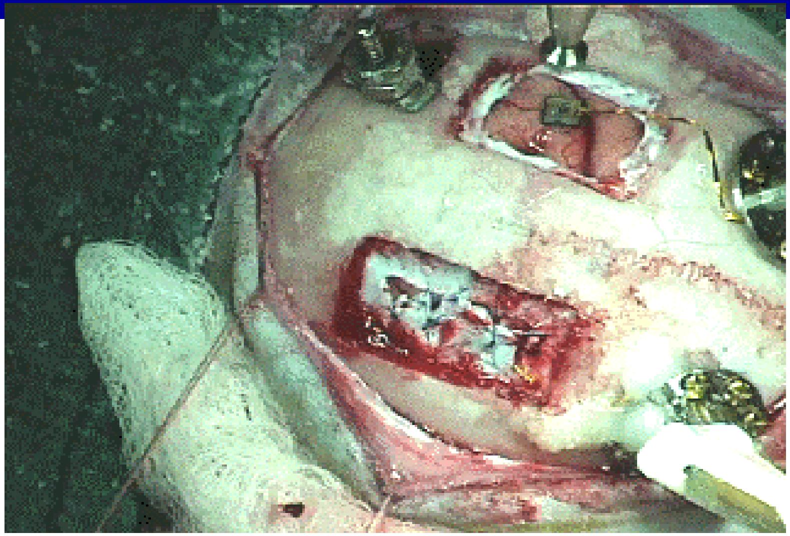
Year 5:

- Demonstration of a proof-of-concept computational device at the Bio/Info/Micro interface with integration of cerebral cortex and nanoelectronics/microphotonics

Technical Example:
Recording and Decoding of Neuronal Ensembles in Motor Cortex



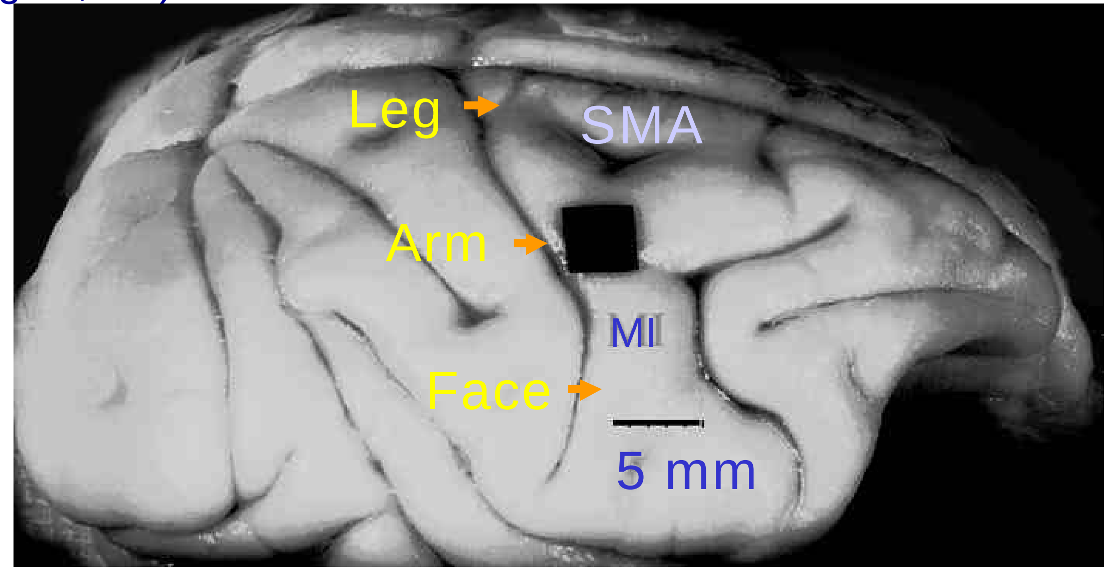
Chronic intracortical multi-electrode array (University of Utah; Bionics Technologies, Inc)

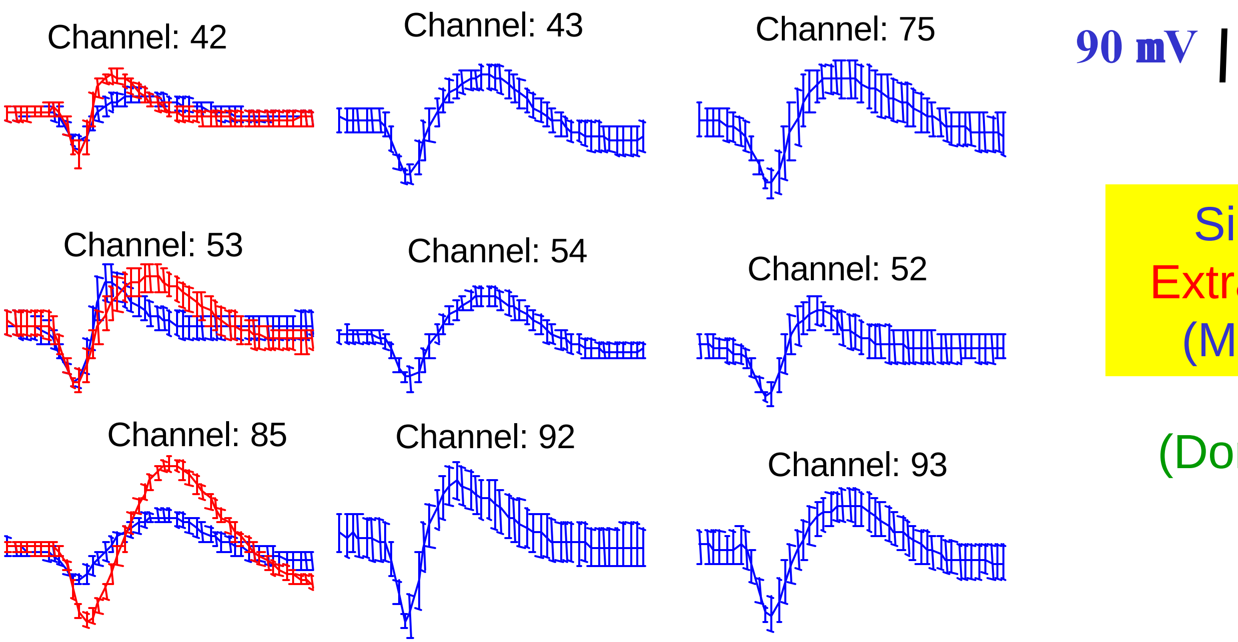


Surgical implantation using a pneumatic impulse inserter

We have performed 18 implants in either primary motor cortex (MI) or supplementary motor cortex (SMA)

(Donoghue, Hatsopoulos et al)

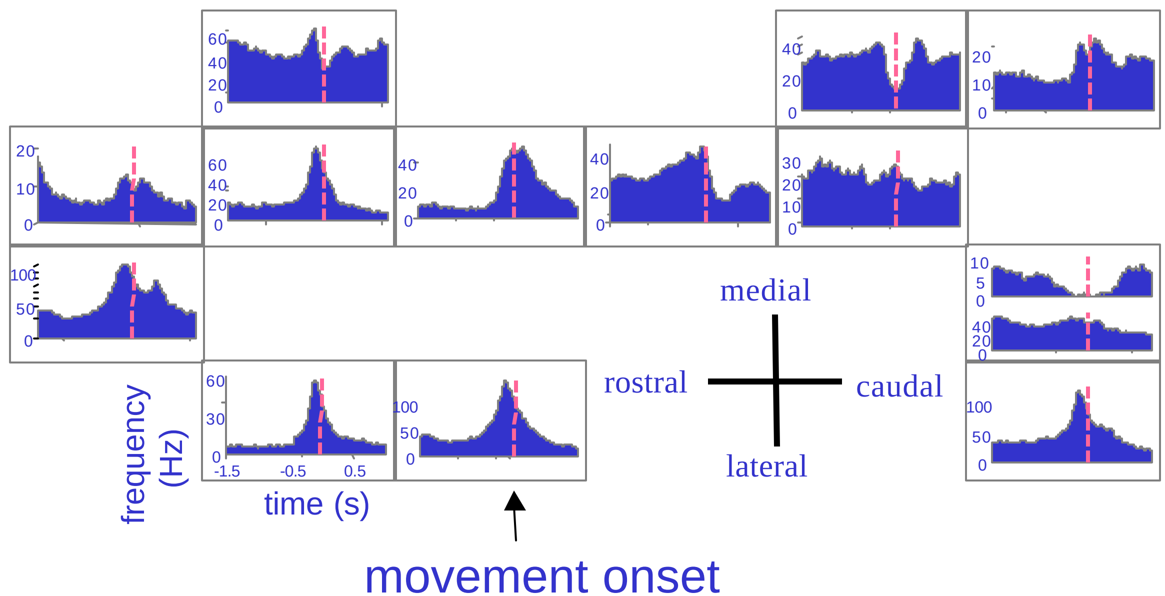




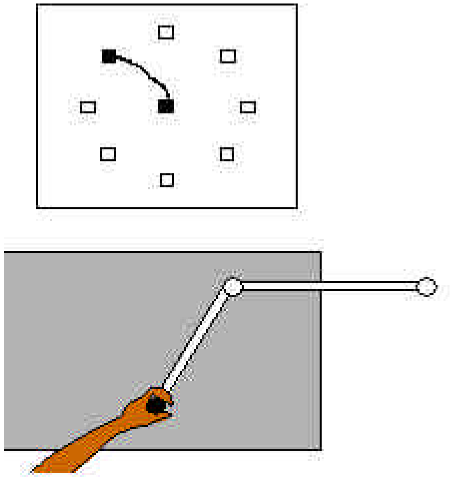
Simultaneously Recorded Extracellular Action Potentials (Mean/Standard Deviation)

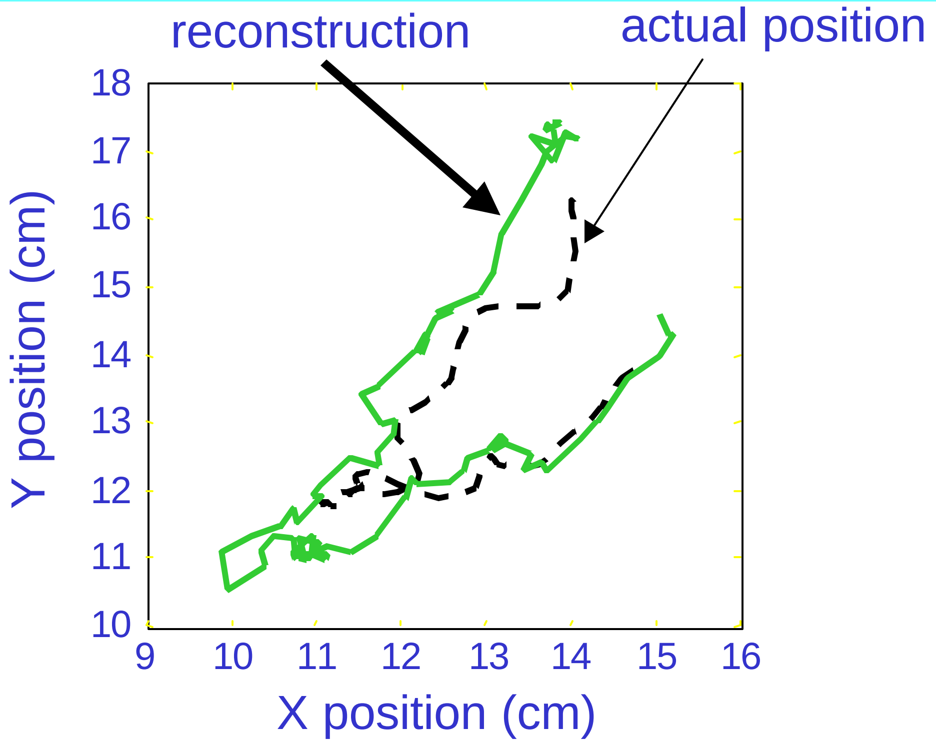
(Donoghue, Hatsopoulos et al)

Activity profiles (peri-movement histograms) from 13 Simultaneously recorded neurons



Decoding of Discrete and Continuous Movements of the Arm Movements to Visual Targets





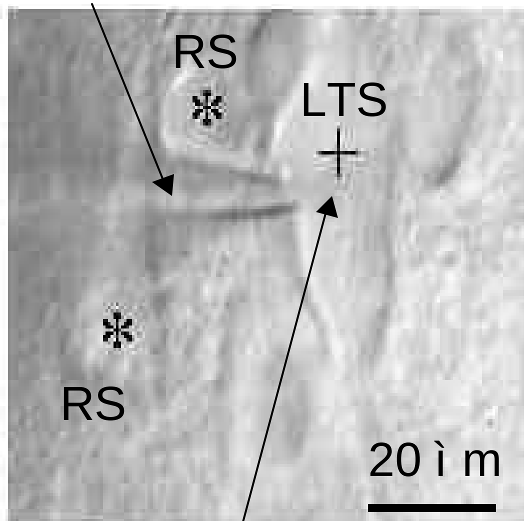
- A chronic physical interface with neural populations is feasible.
- Signals from randomly selected motor cortical neurons provide extensive information about discrete motor behaviors as well as continuous movement parameters (hand trajectory)
- Decoded cortical signals can be used to drive physical devices (robot arms, computer cursors) in ~real time.

Technical Example: Electrically coupled networks of neurons: Inhibition, rhythms, and synchrony

neocortex

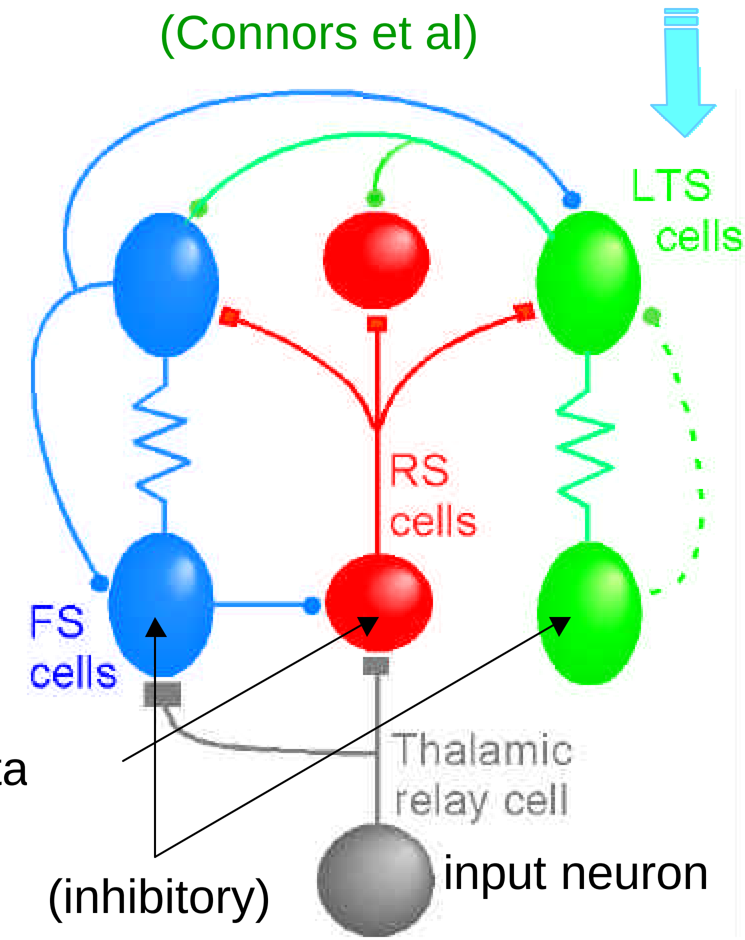
thalamocortical slice
in the recording chamber

microelectrode
(linear array)



fast spiking
interneuron

(excita

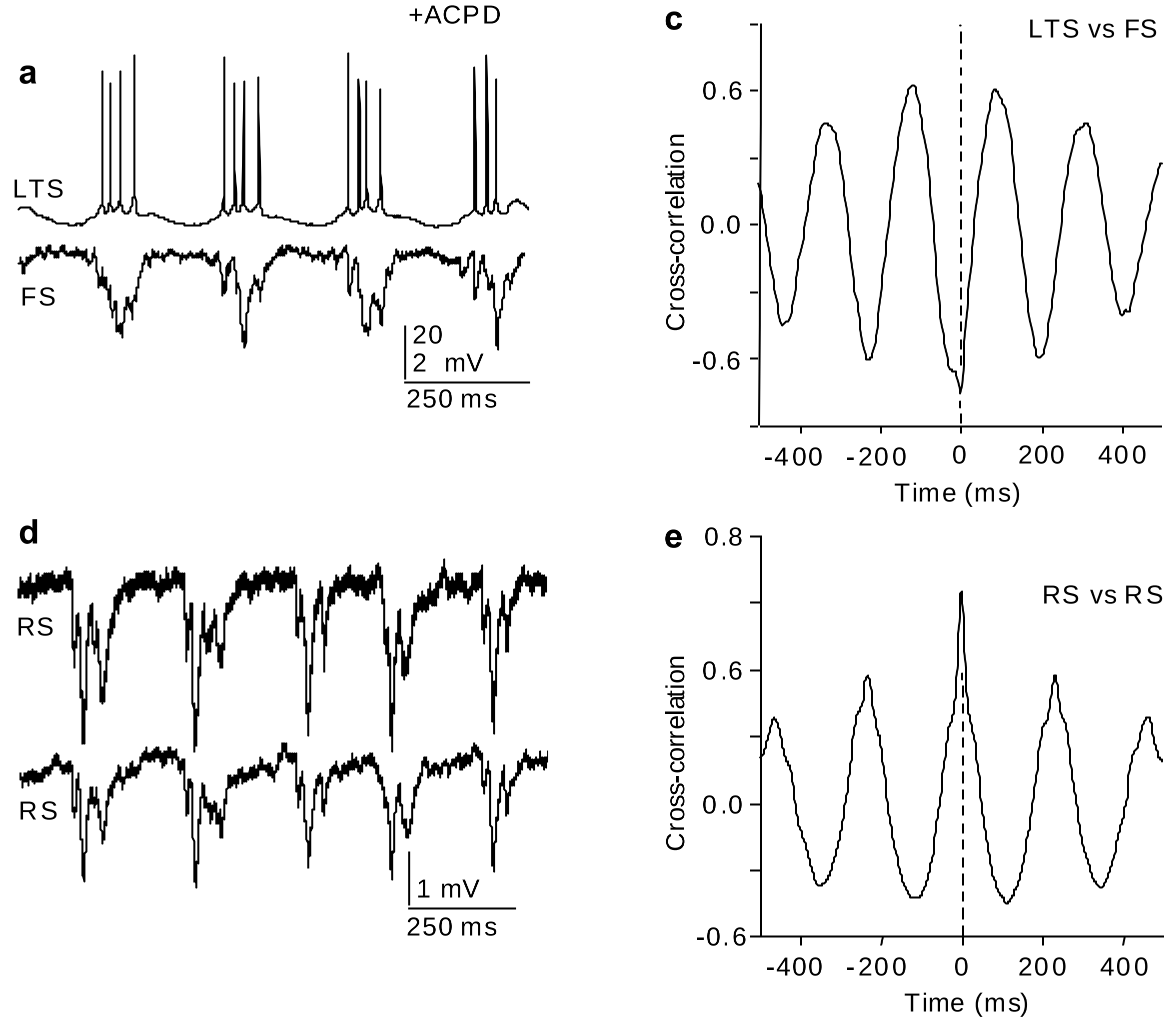


(inhibitory)

input neuron

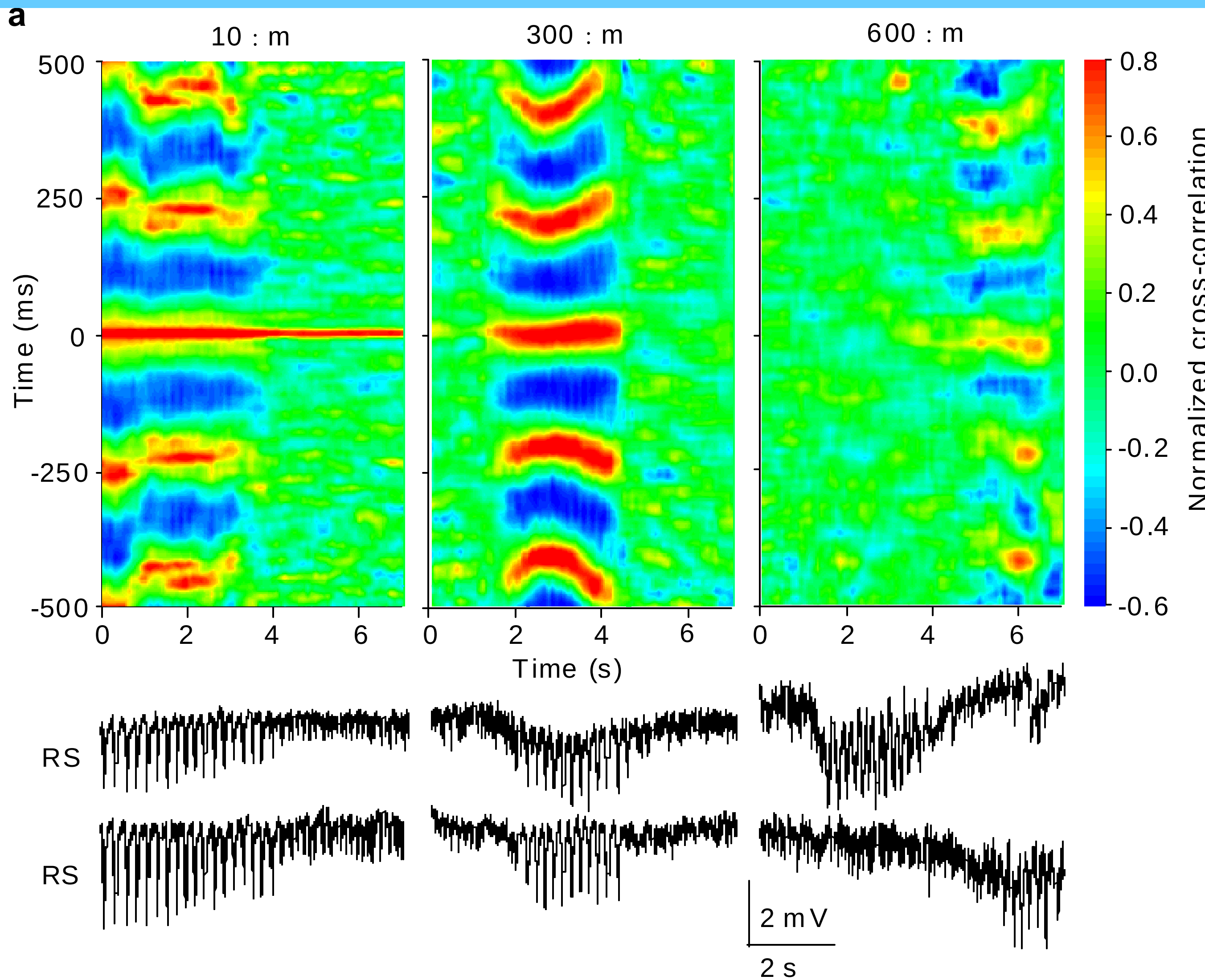
Information dynamically represented by correlated
pattern of activity in small groups of neurons

The activated, synchronized LTS network generates strong inhibitory potentials in other neurons in the local circuit (top); inhibition is itself synchronized across the circuit (bottom).



Connors et al (2000)

Synchrony of rhythmic inhibition ranges over a wider spatial domain of cortex than does irregular inhibitory patterns



Technical Example: Nanoelectronic Interactive Probes in Coupled Neural and Nano Systems

- new generation of large area, high spatial resolution electrical (potential) probes

Neuronal Probing and Probe Design using Carbon Nanotubes Arrays

- In vivo recordings.
- In vitro recordings.
- High spatial resolution, broad area coverage. compatibility with Si electronics, high conductivity, strength, chemical inertness, and flexibility

Explorations of Systems Couplings

- Neuronal correlation / Passive recordings.
- Active recordings via neuronal stimulation
- Bio-neuronal and Nanoelectronic Intersystem Super-Coupling

Collective Behavior

↓

Nanoelectronic

↓

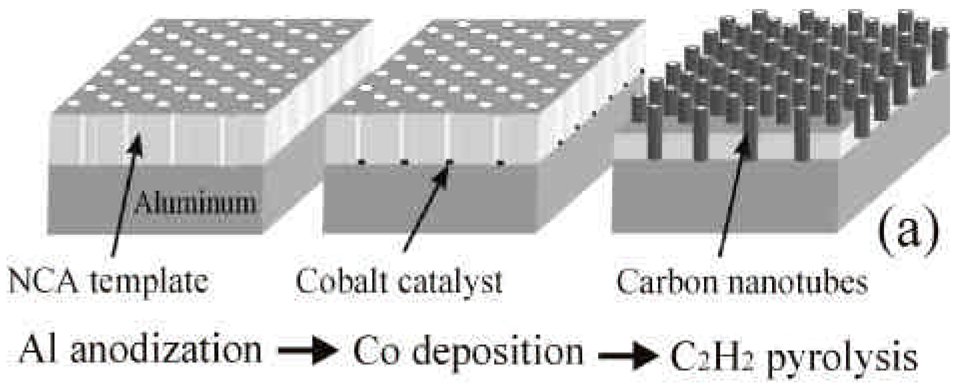
Nanoelectronic under the influence of imported bio neural connectivity

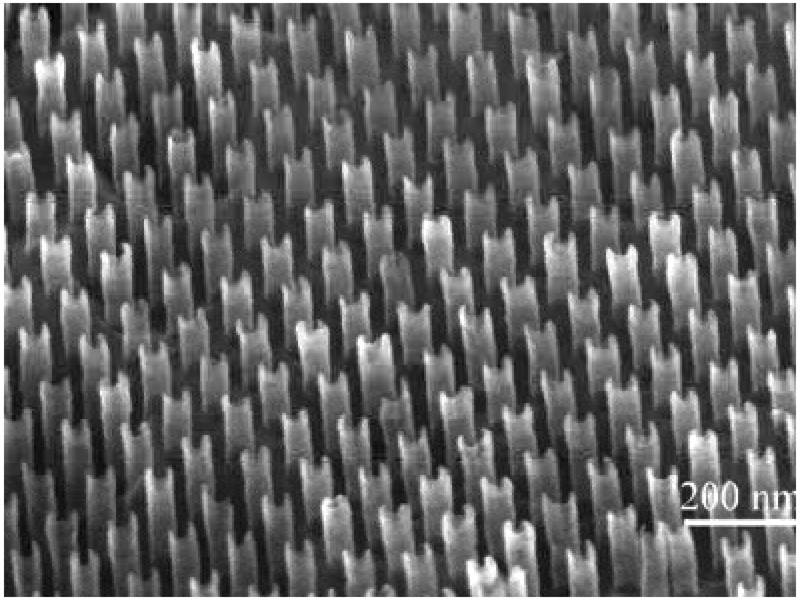
↓

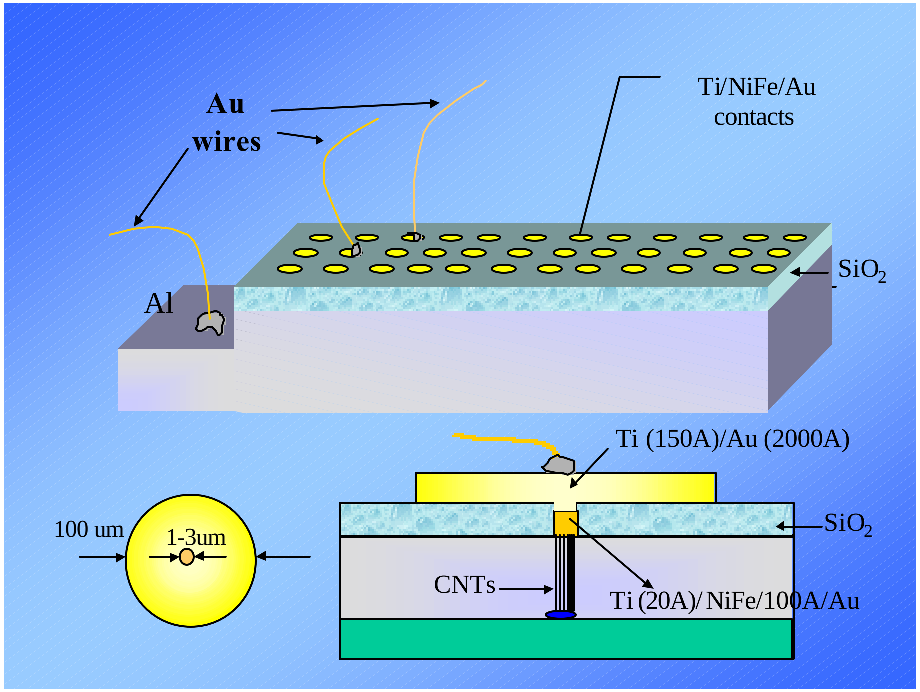
Non Von Neumann Computing ?

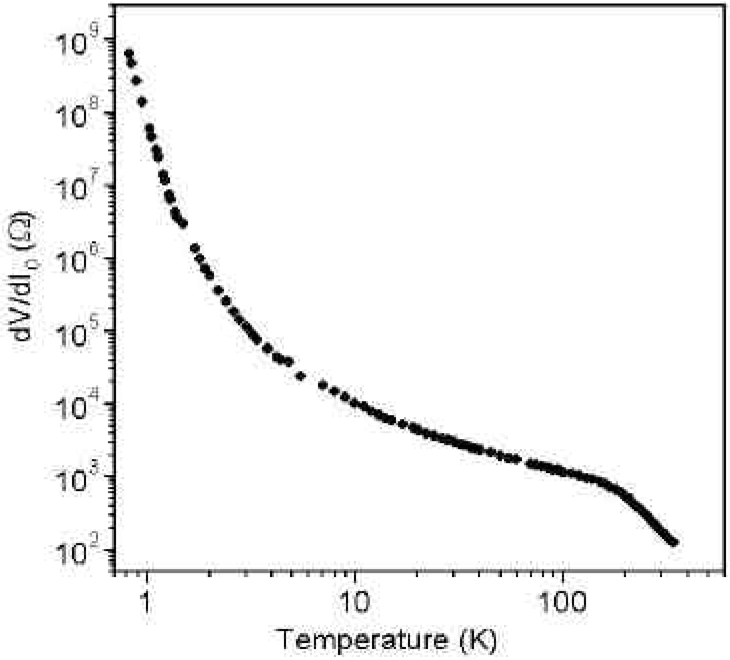
(J. Xu et al)

(J. Xu et al)

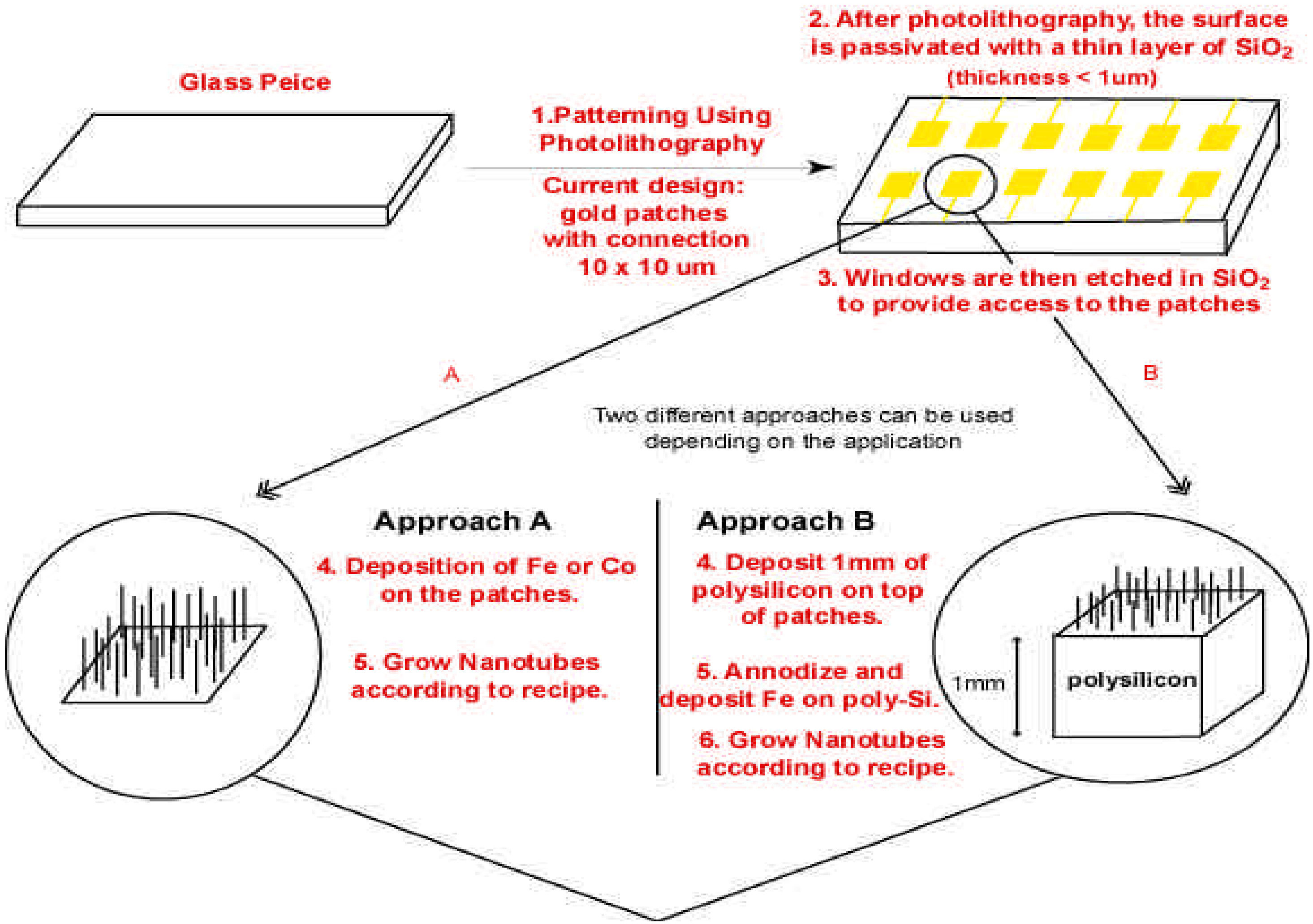

Aluminum
(a)
NCA template
Cobalt catalyst
Carbon nanotubes
Al anodization → Co deposition → C2H2 pyrolysis


200 nm

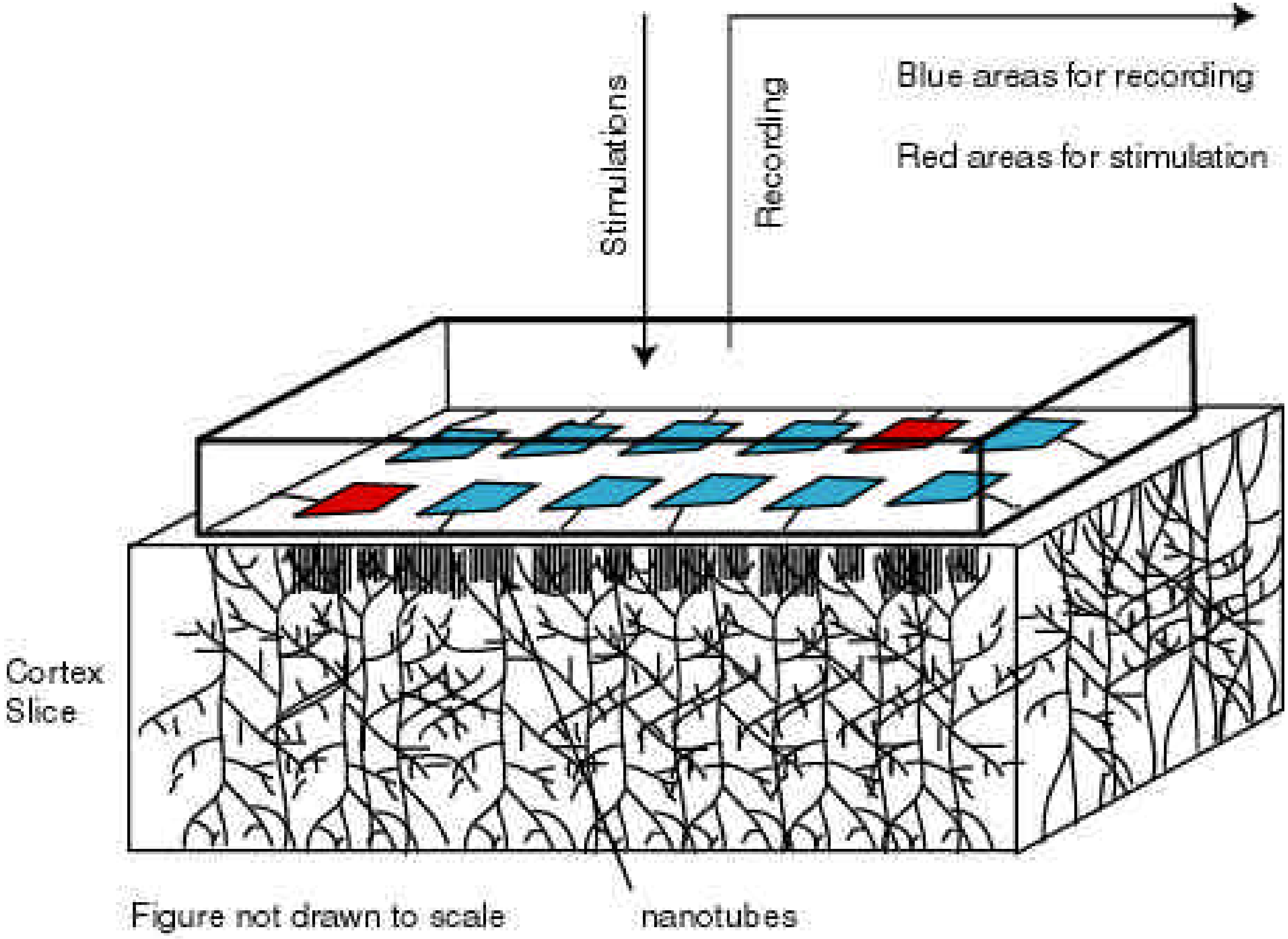

Au
wires
Ti/NiFe/Au
contacts
Al
SiO2
Ti (150A)/Au (2000A)
100 um
1-3um
SiO2
CNTs
Ti (20A)/ NiFe/100A/Au


dV/dI0 (Ω)
Temperature (K)
1
10
100

Probe Design: Two Approaches



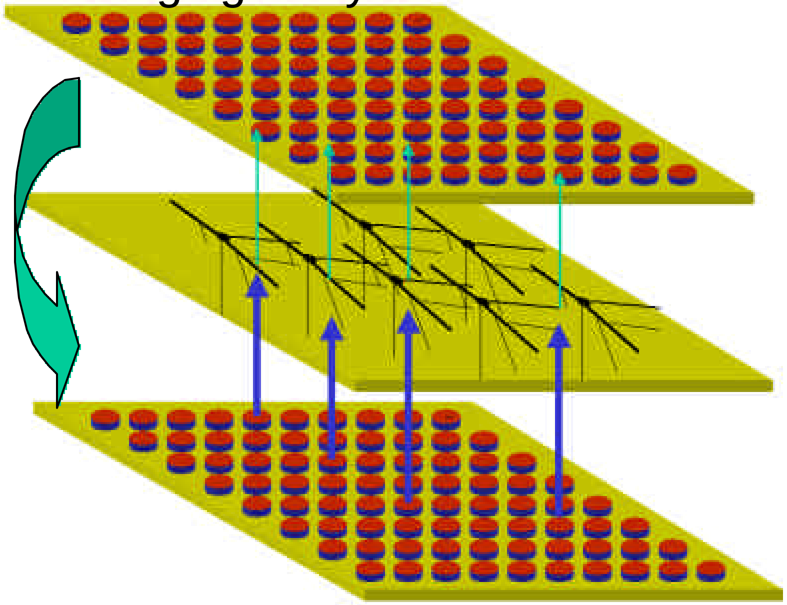
System Design: The Probe at the Bio/Nanoelectro Interphase



Technical Example: Microphotonic Arrays for Interactive Imaging of Cortical Circuitry

<u>Goal</u>: establish a two-way "wireless" communication between neural networks and high speed, large scale optoelectronic probe/excite arrays (Nurmikko et al)

imaging array



transducer array

- study and exploit collective, long range interactions in context of parallel processing
- new (and unique) technology element: blue/NUV compact semiconductor light emitters (LEDs, diode lasers)

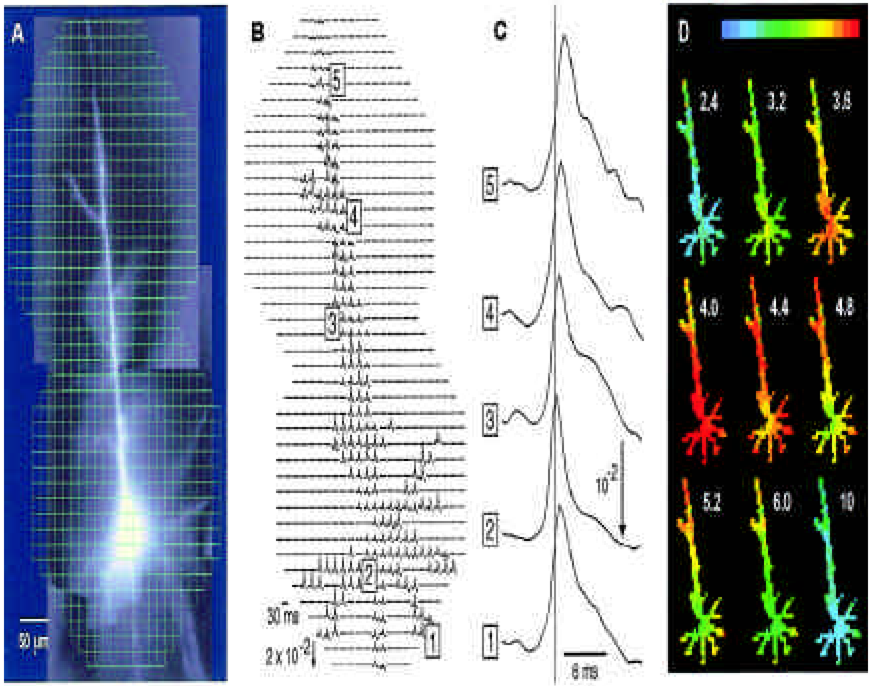
LED/laser and photodiode arrays:

- High spatial resolution (<10ì m)
- High speed (<<msec real time)
- Large area arrays (>mm^2)

- monolithic integration of ultracompact microphotonic transducer/receiver arrays

Current Use of "Photonics" in Neurobiology

S. Antic et al J. Neurophys. 82, 1615 (1999): vertebrate neurons in brain slices



(a) Imaging of action potentials of single neurons

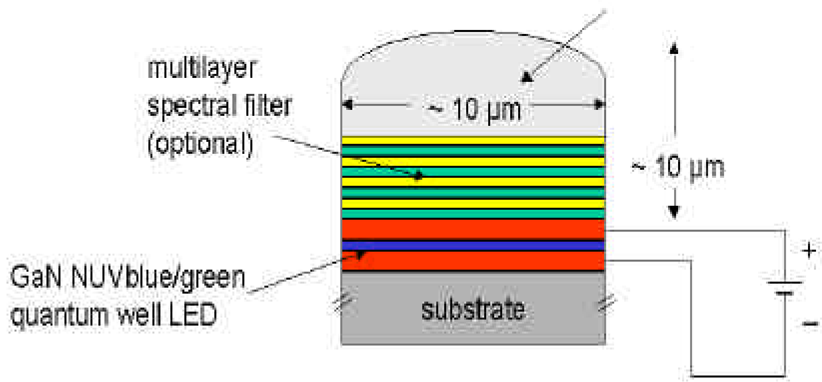
(b) Optical probing of neuronal circuits

- voltage sensitive dyes
- Ca^{2+} sensitive indicators

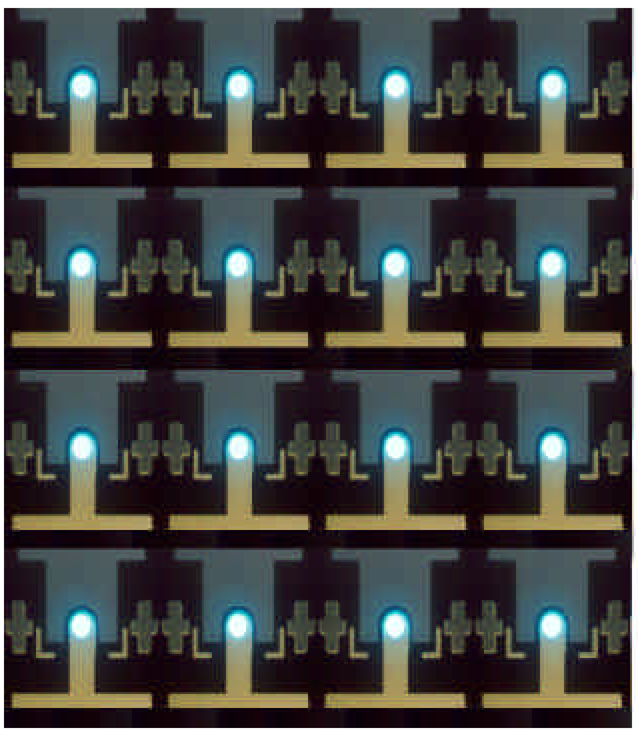
(c) Photostimulation of neuronal activity (e.g. photolysis of caged glutamate)

→ need of compact NUV/deep blue light sources

Our approach: compact, high intensity, programmable arrays of planar GaN-based NUV/blue/green semiconductor LEDs and lasers



Rudimentary Array of Blue LEDs
(20 ì m dia; ë=460 nm)

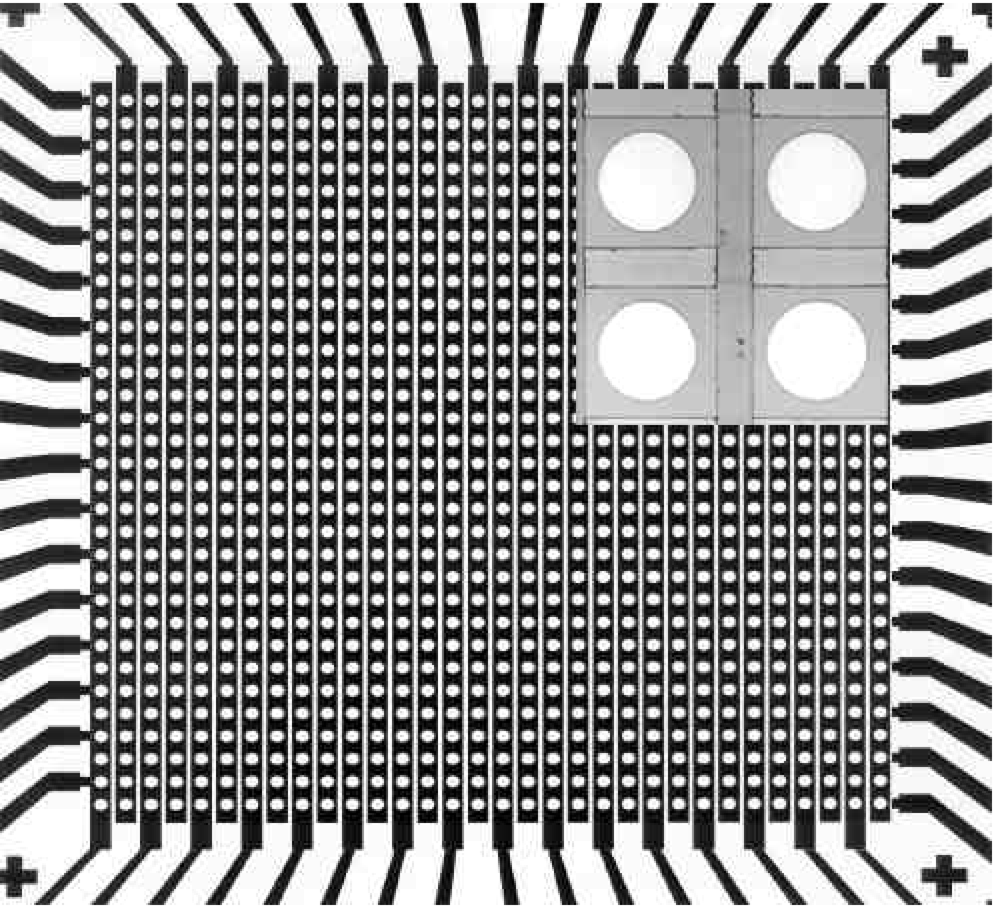


Blue/NUV Light Emitting Diodes: ultracompact sources for fluorescence imaging and photoexcitation of neurons

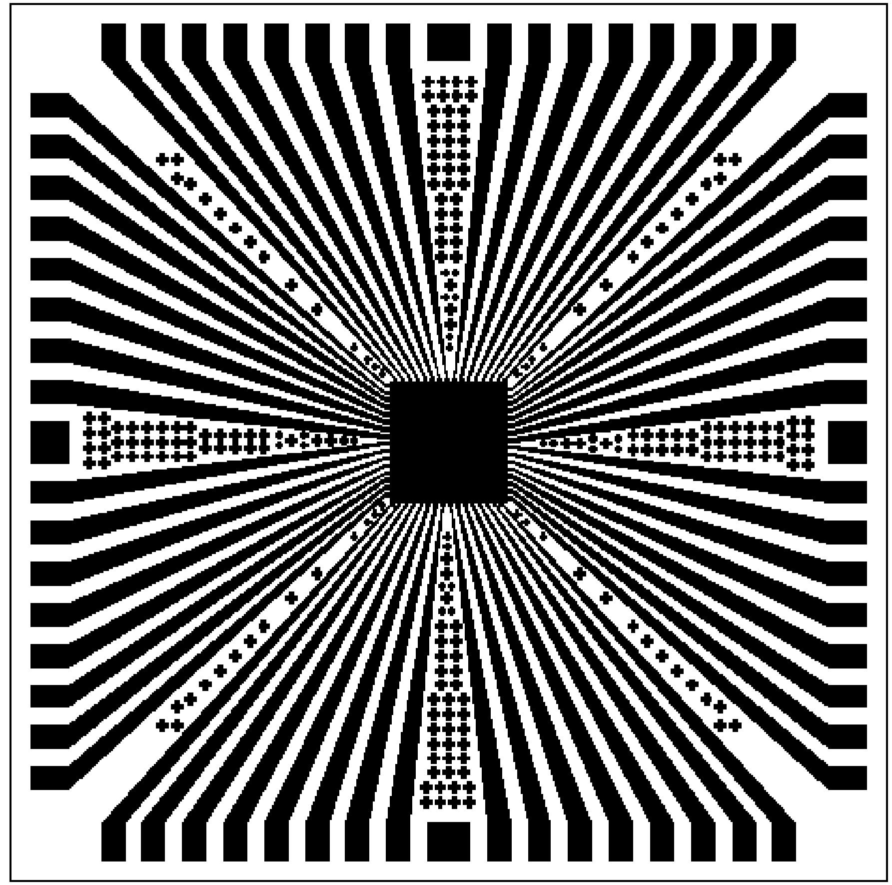
- InGaN/GaN quantum well semi-conductor heterostructures
- planar processing technology
- wavelength range 370-520 nm
- employed in time resolved spectroscopy (cultured cells)
- output powers up to >10 mW (20 micron diameter)
- current progress towards microcavity devices: RCLED and VCSELs for added spatial and temporal coherence
- compatible with large array design and processing

presently: 1024 element array

Next Generation of Blue LED Arrays for Cortical Imaging



LED array layout



Electrical (contact) layout

- 32x32 element individually matrix addressable array (1024 LEDs)
- 10 ì m individual device diameter, 50 ì m spacing, ~ 1.5 mm^2 total area

Technical Example: Computation with Massive Parallelism: The Nervous System and Nanostructures

Anderson, Kimia

Objective: Modeling Neuronal Activity and Spatial Computation while developing needed theoretical support to the analysis and understanding of experimental input provided by the new sensor/transducer nanoarrays

Present Status and Issue:

rare for high level neural theory to interact with physical level experimental observations due to lack of detailed spatial and temporal recording over a large neuron ensemble

We have two types of modeling approaches to spatially extended computation: both get most of their power from the lateral propagation of information and formation of "interference patterns" when propagating information collides

(a) "network of networks" (Anderson): an array of elementary units that are small nonlinear attractor neural networks and interact locally with neighbors

(b) "shockwave" based spatial computational technique (Kimia) for object recognition as means of forming "symmetry based" representations

Notes (general):

Traditional computers do not compute what we do:
Different hardware leads to different engineering solutions.

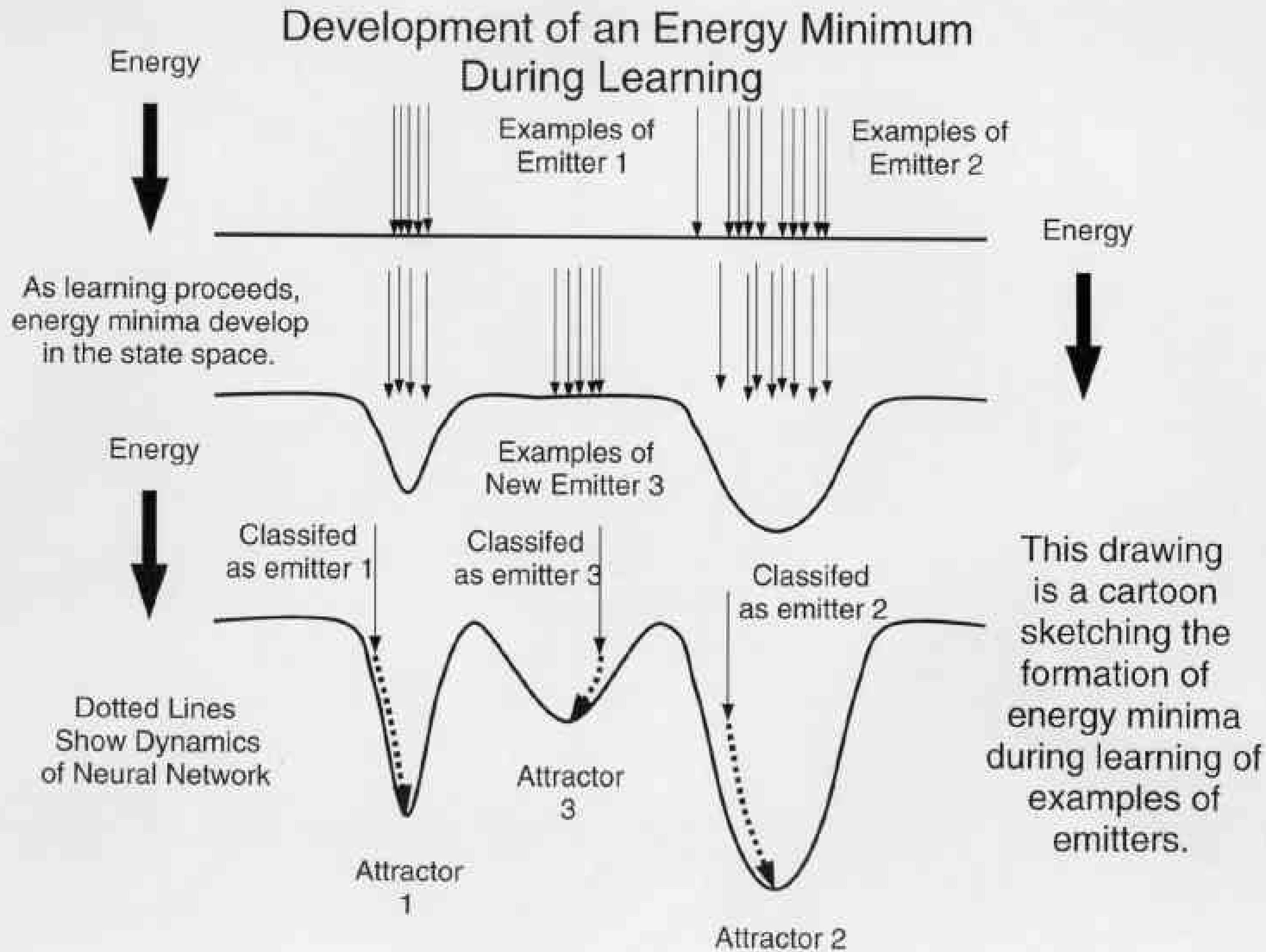
- Computers are good at: Excel spreadsheets, bank balances, boring detail (trees)

- Human-like computers are good at: intuition, association, plausible inference (forests).

Nanostructures or any brain-like computational architecture will build “human like” computers.

One current approach to “cognitive computation” uses properties of dynamical systems with attractors as a way to do computation.

Radar Signal Classifier : Who is watching me?



The "Network of Networks" (J. Anderson, and J. Sutton, Harvard)

- Neurons (single units) are not the elementary unit of neural computation but groups of neurons are.

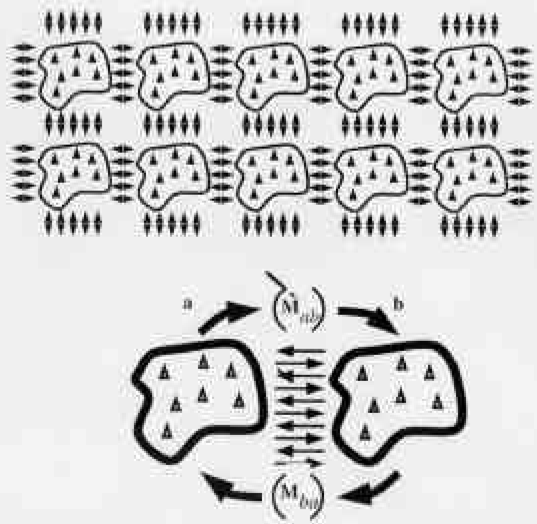
- Small attractor networks are the basic functional units (single units are only of interest in as they give rise to the distributed activity patterns in the attractor networks)

- Attractor networks connect and states in one network propagate into neighbors. "interference patterns" formed when patterns collide become key information processing elements. They are formed from combinations of lower level features

  - discretize underlying geometry
  - architecture found e.g. cortical colums (mammals

Interacting groups of attractor networks form the basic computational unit of the network of networks. (a)

Module interactions are governed by the "state interaction matrix" which governs the strength of interaction between modules. (Generalized connection strengths.) (b)

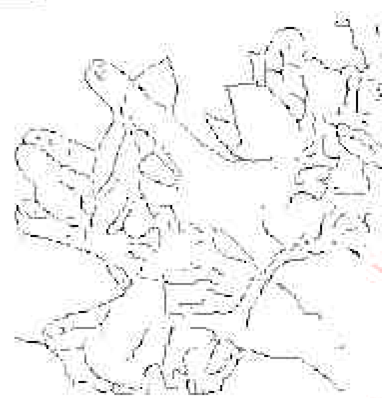


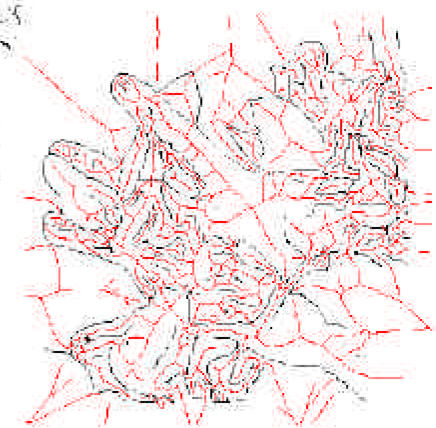
Wave-Propagation: A Computational Paradigm (B. Kimia)

We have developed a computational paradigm for vision that relies on

- Wave Propagation (Eikonal Equation)
- Interference Patterns or Shock Waves
- Transformation of these patterns
- Detection of optimal paths of transformation

"Shock wave" model: Technique for deriving and representing spatial relationships among edge elements

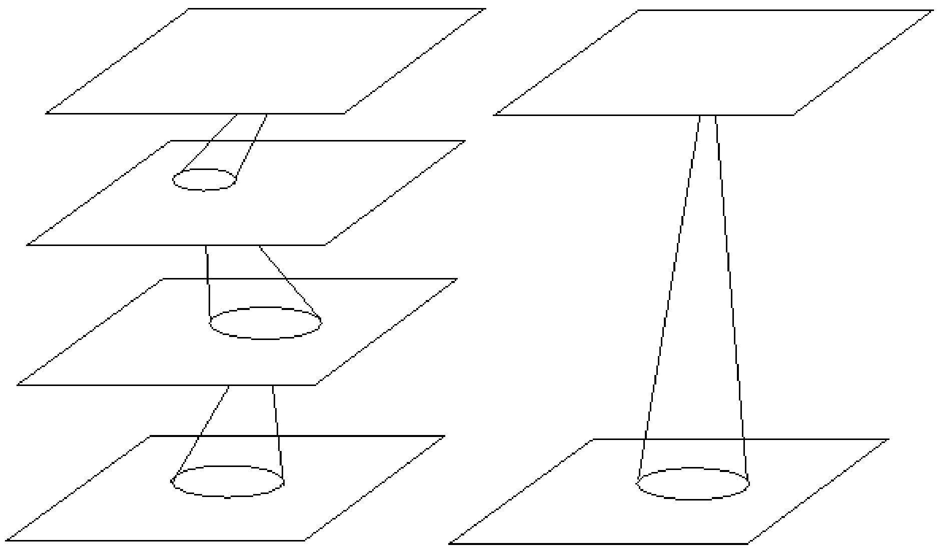




The need to organize "geometrically" related structure is not unique to vision, but also applies to other domains such as touch and sound, as well as motor maps.

The Neural Connection

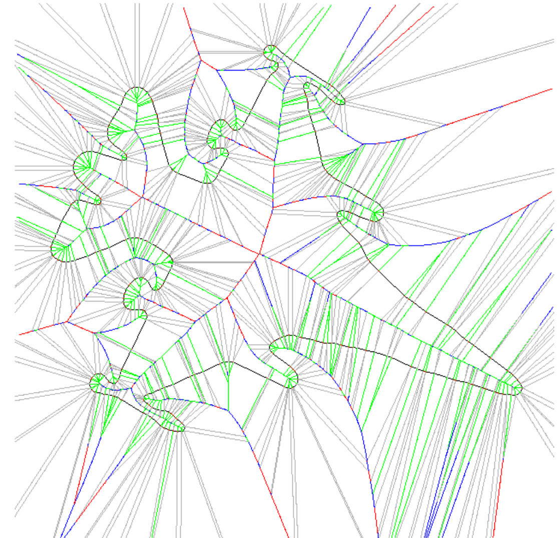
- The proposed framework requires intra-layer "horizontal" activity as well as inter-layer "vertical" activity.
- Intra-layer wave propagation proposed here is intriguingly consistent with existing psychophysical evidence and neurophysiological recordings.
- Traditional Receptive Field (RF) models is equivalent to "convolution" or parabolic PDE models.



Goals

- Parallel implementations of wave propagation and corresponding experiments take into account neuronal circuit constraint

- Provide a model to seek dynamic activity in large scale recording
  - evidence of interference pattern
  - shock wave propagation
  - role of scale



- Extend model to spatially variant Eikonal equation
  - account for propagation velocity variations
  - dependence on local context
  - region based segmentation

- Interactions between the "shockwave" and the "network of networks" models.