How Biological Information Processing May Have Correlates with Quantum Information Processing and How You Could Build Such a System

Presented by

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And of Chemistry, Biomolecular Science and Electrical Engineering

How to set the argument

• Computers were originally created to break codes and carry out functions of humansperforming manual computation and probabilities

• In effect to take over function of human information processing but at a simplistic Level

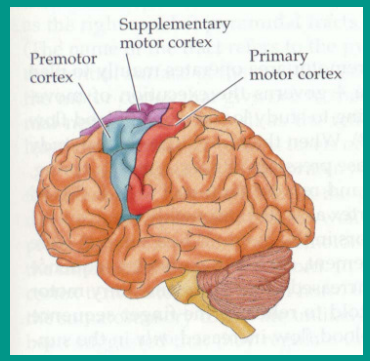
• With time, scientists wanted to reproduce more human capabilities using these systems and along the line definitions became hazy

• Artificial intelligence is one of the ultimate goals of computer science

• I I believe artificial intelligence is NOT really computation
    • really advanced information processing
    • early on the decision was made to attack this problem software design at the expense of hardware
    • I believe this was a fundamental error as it has led to little progress towards real AI over the last 40 years

• I think looking at the biological hardware is the key to future progress

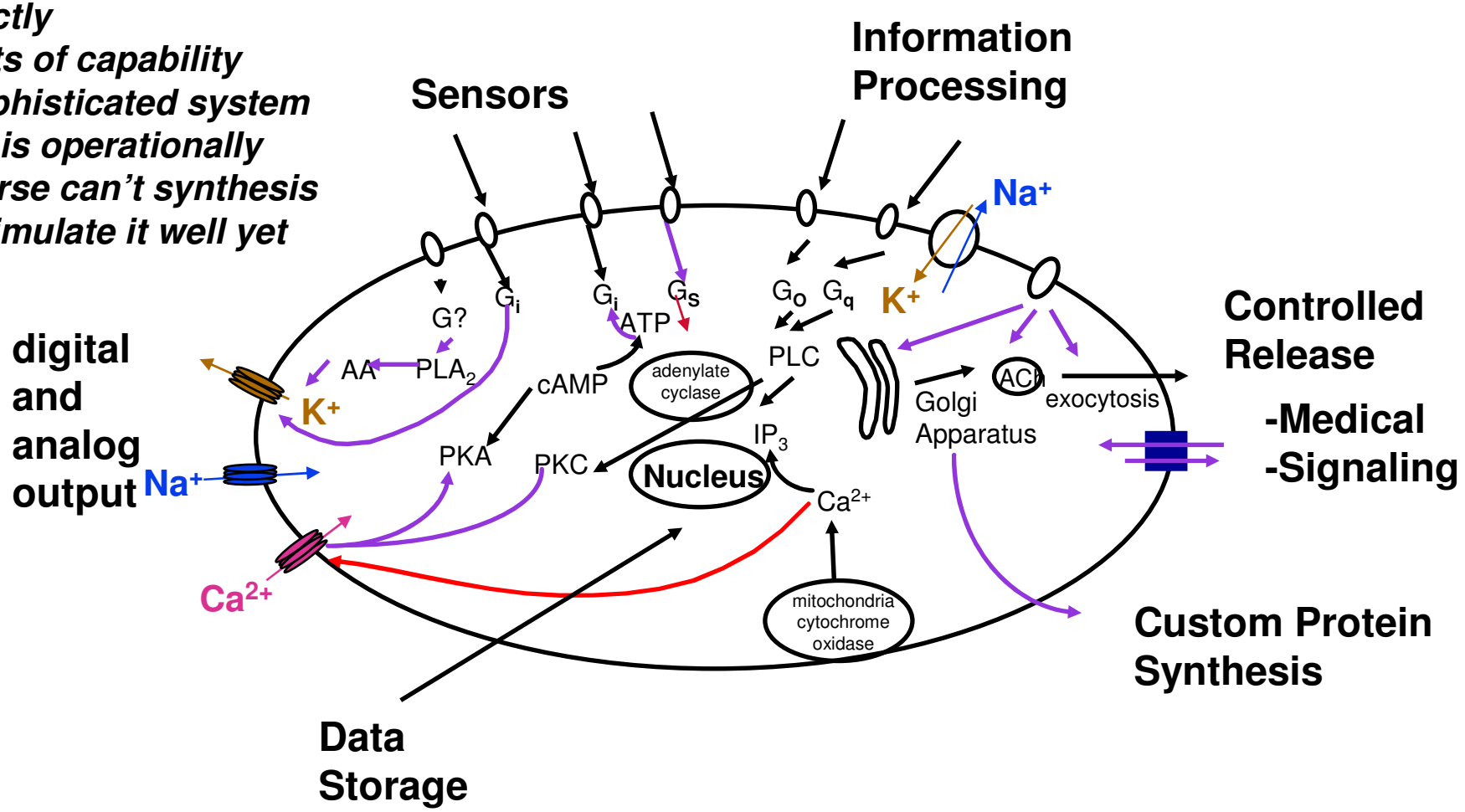
Biological Circuits, Signals and Systems

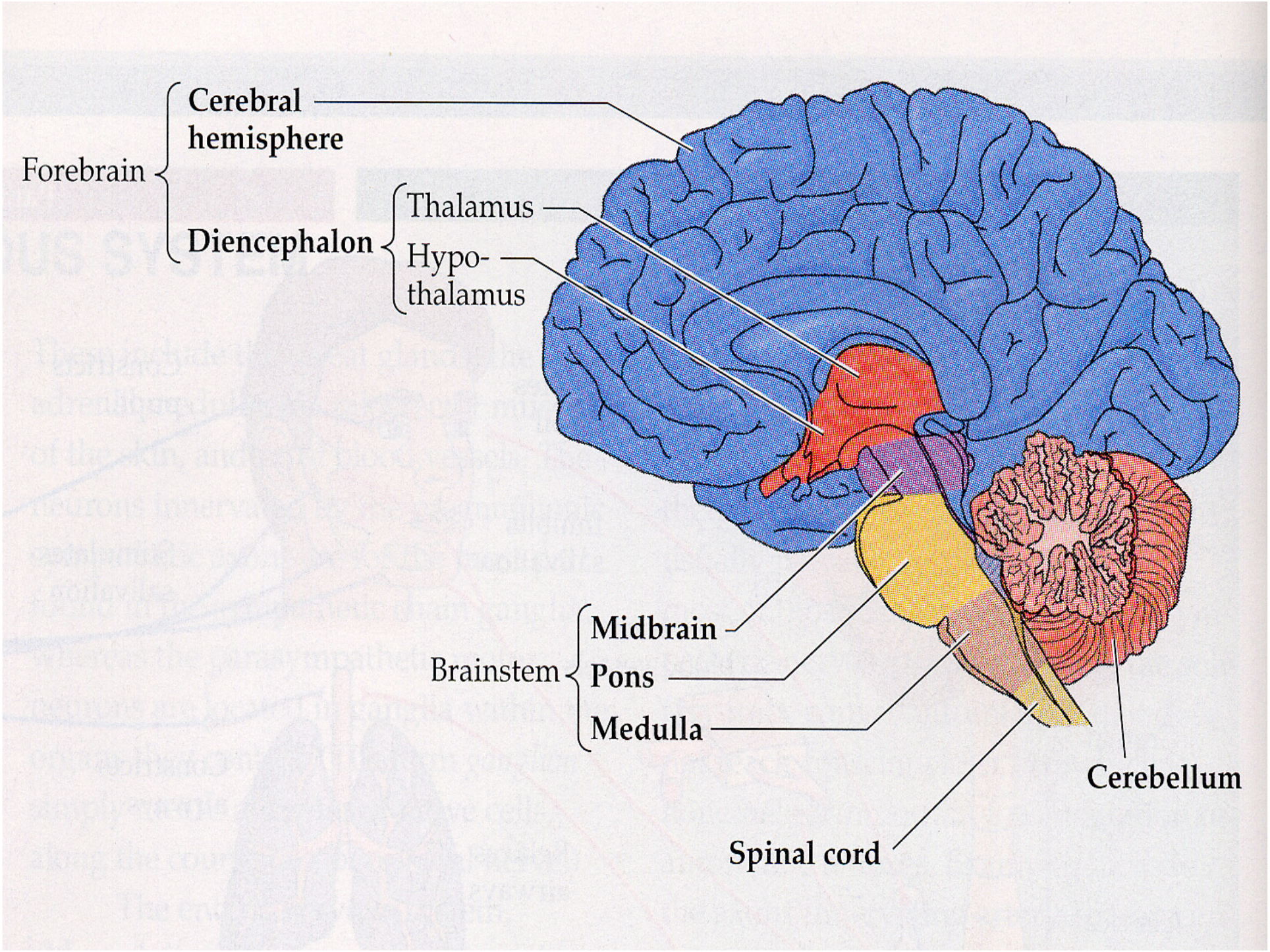


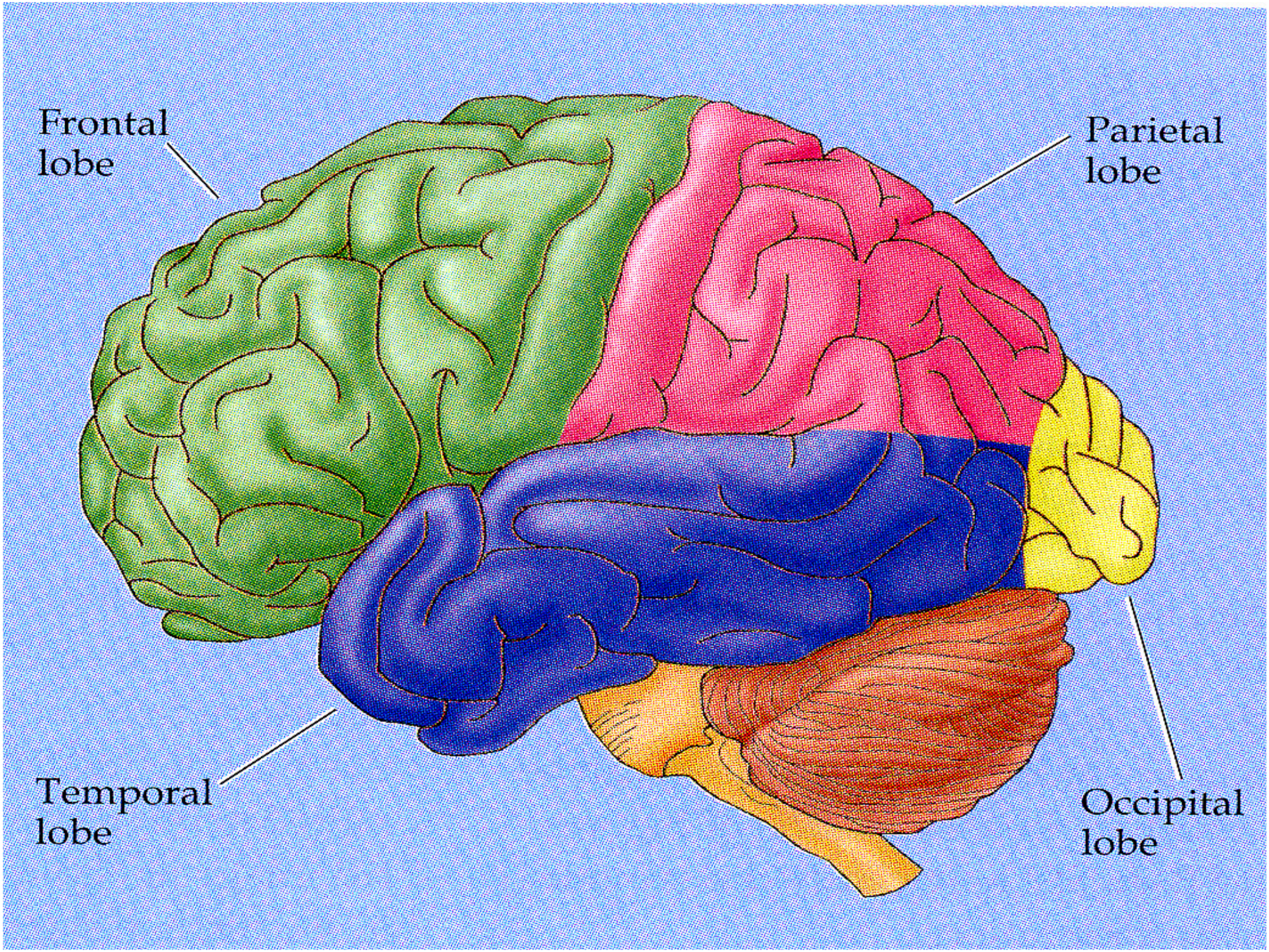
System	# Neurons	Function
Spinal Cord	2	Monosynaptic Reflex
Spinal Cord	4 - 5	Polysynaptic Reflex
Pain Sensation	5 - 10	Pain
Lobster Digestive System	17	Nutrient Processing
C. Elegans	302	Life
Leech	400	Pattern Recognition
Crayfish	90000	Life
Octopus	1×10^8	Swimming
Olfactory Cortex (Mammalian)	1×10^8	Pattern Recognition (Memory Storage)

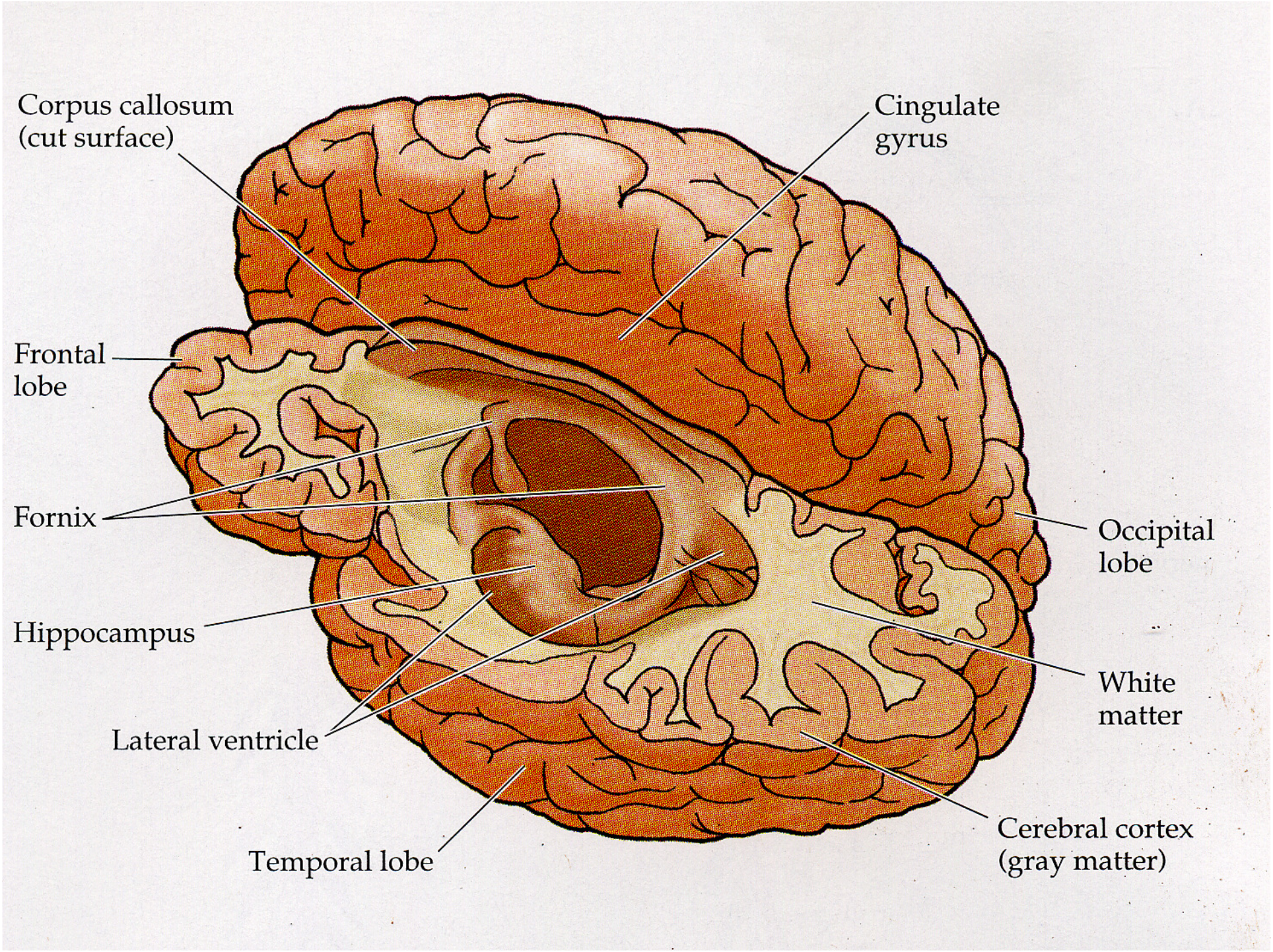
Cellular Subsystems are also Important

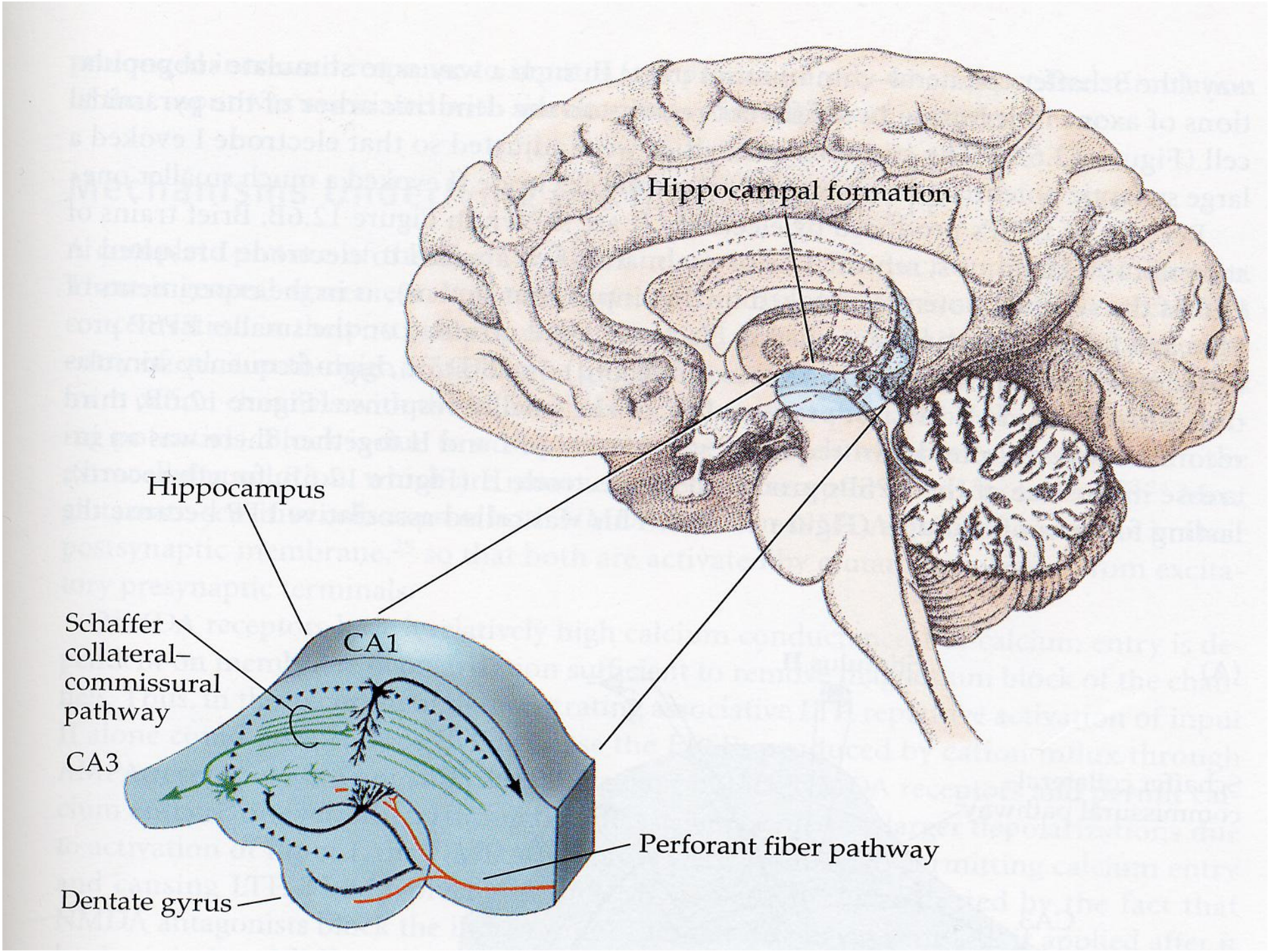
-Useful to program cells directly
-- lots of capability
- sophisticated system that is operationally diverse can't synthesis or simulate it well yet

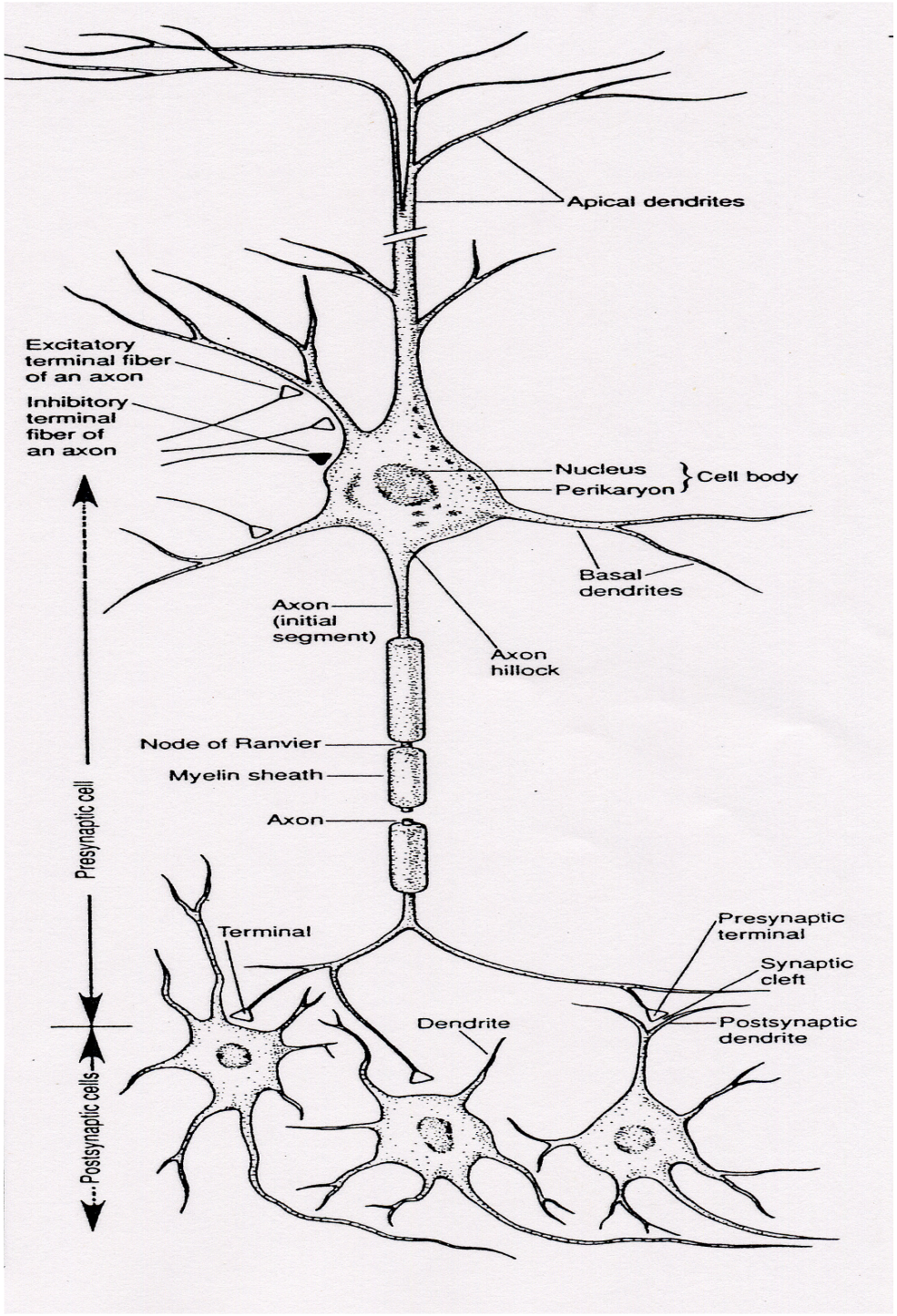



Forebrain
Cerebral hemisphere
Diencephalon
Thalamus
Hypo-thalamus
Brainstem
Midbrain
Pons
Medulla
Cerebellum
Spinal cord


Frontal lobe
Parietal lobe
Temporal lobe
Occipital lobe


Corpus callosum
(cut surface)
Cingulate
gyrus
Frontal
lobe
Fornix
Occipital
lobe
Hippocampus
White
matter
Lateral ventricle
Cerebral cortex
(gray matter)
Temporal lobe


Hippocampal formation
Hippocampus
Schaffer
collateral–
commissural
pathway
CA1
CA3
Perforant fiber pathway
Dentate gyrus



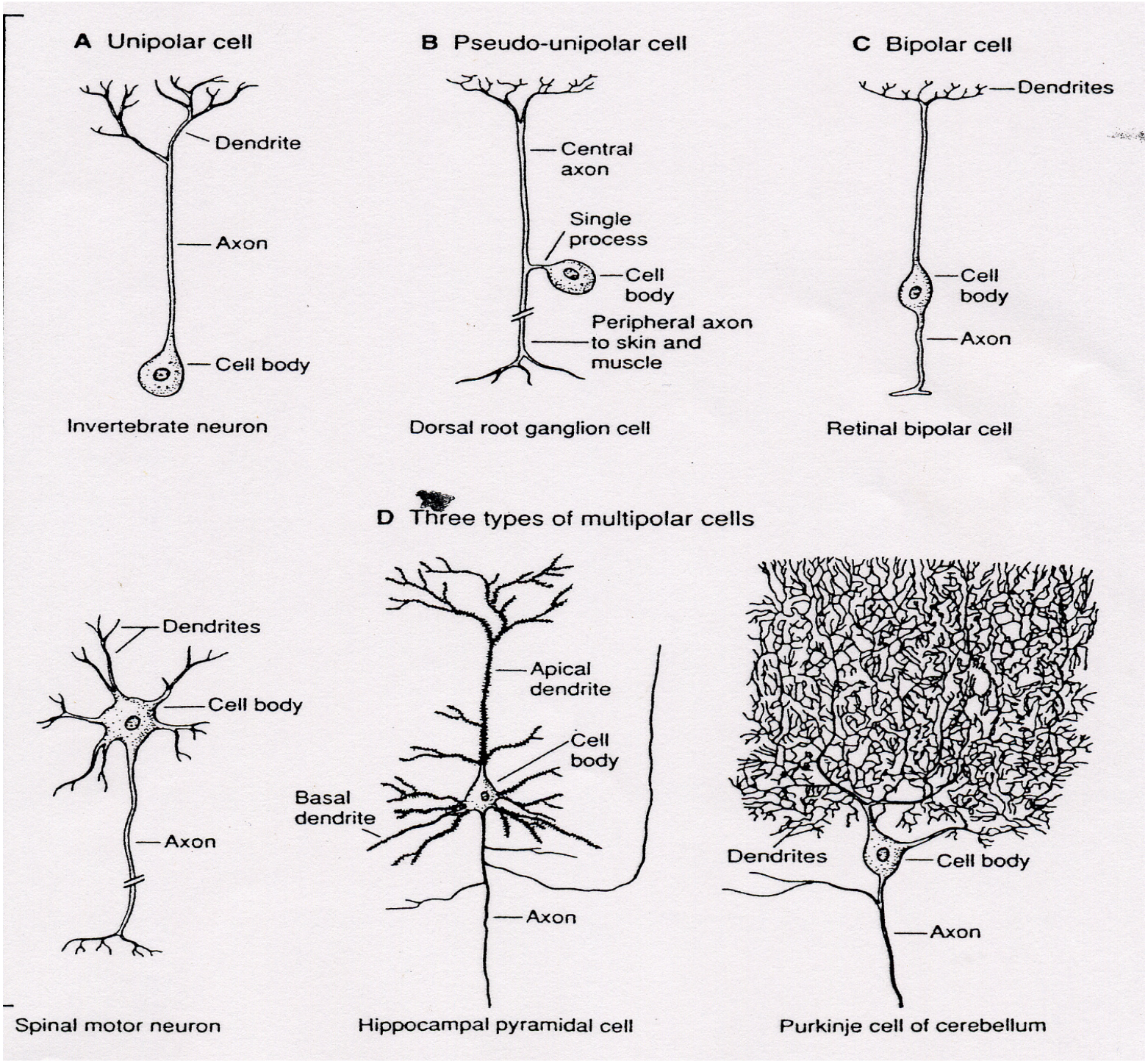
Information in the nervous system generally, but not always, flows from the dendrites to the axon.

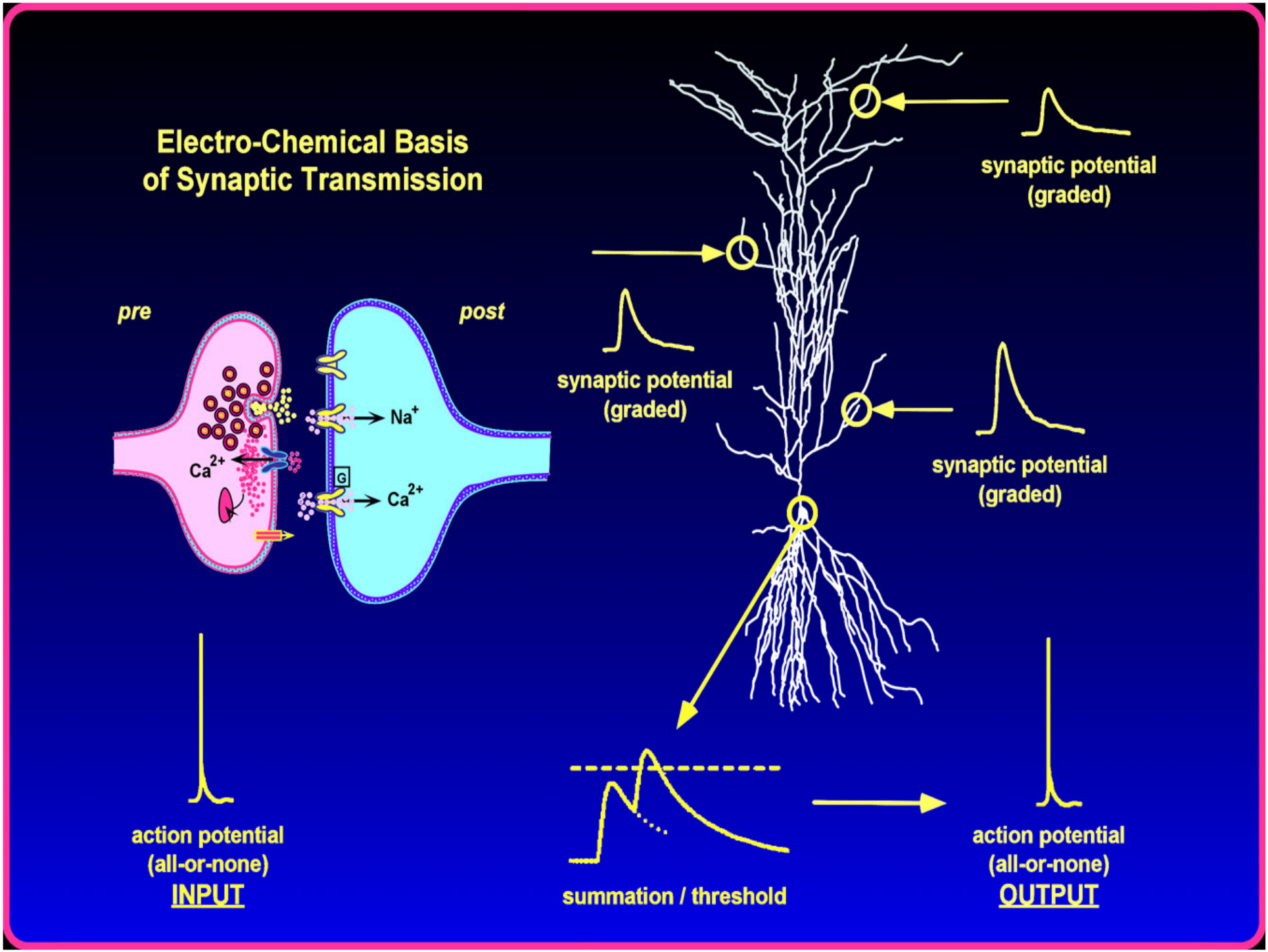
Action potentials are initiated at the beginning of the axon in an area called the axon hillock.

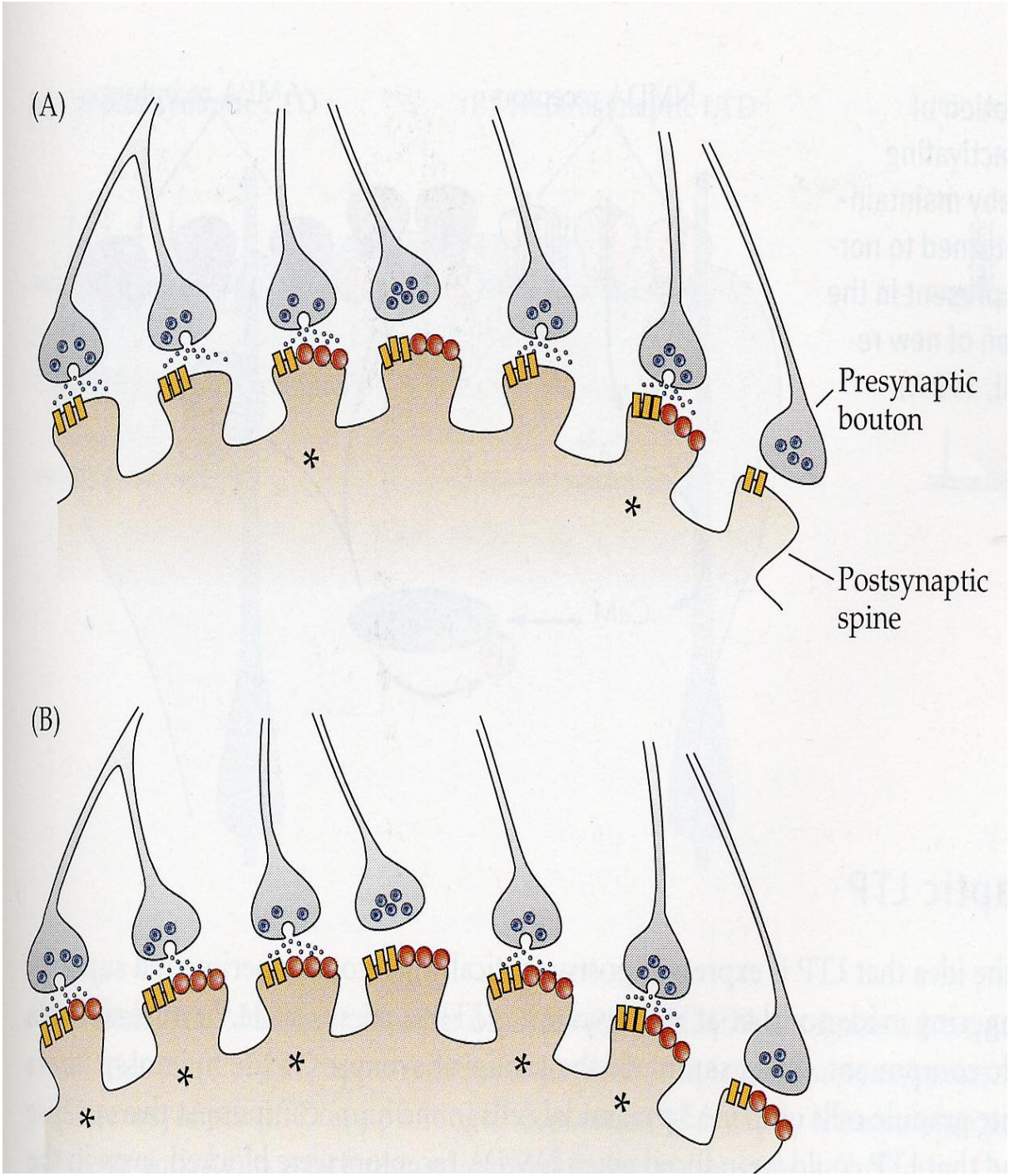
This area contains a higher density of voltage-activated Na^+ channels than the rest of the cell.

It also has a high input impedance than the cell body because it is narrow region of the cell.

After the action potential is initiated, it back propagates to the cell body and dendrites and propagates forward to the axon terminal.


A Unipolar cell
Dendrite
Axon
Cell body
Invertebrate neuron
B Pseudo-unipolar cell
Central axon
Single process
Cell body
Peripheral axon to skin and muscle
Dorsal root ganglion cell
C Bipolar cell
Dendrites
Cell body
Axon
Retinal bipolar cell
D Three types of multipolar cells
Dendrites
Cell body
Axon
Spinal motor neuron
Apical dendrite
Cell body
Basal dendrite
Axon
Hippocampal pyramidal cell
Dendrites
Cell body
Axon
Purkinje cell of cerebellum


Electro-Chemical Basis
of Synaptic Transmission
pre
post
Na+
Ca2+
G
Ca2+
synaptic potential
(graded)
synaptic potential
(graded)
synaptic potential
(graded)
action potential
(all-or-none)
INPUT
summation / threshold
action potential
(all-or-none)
OUTPUT



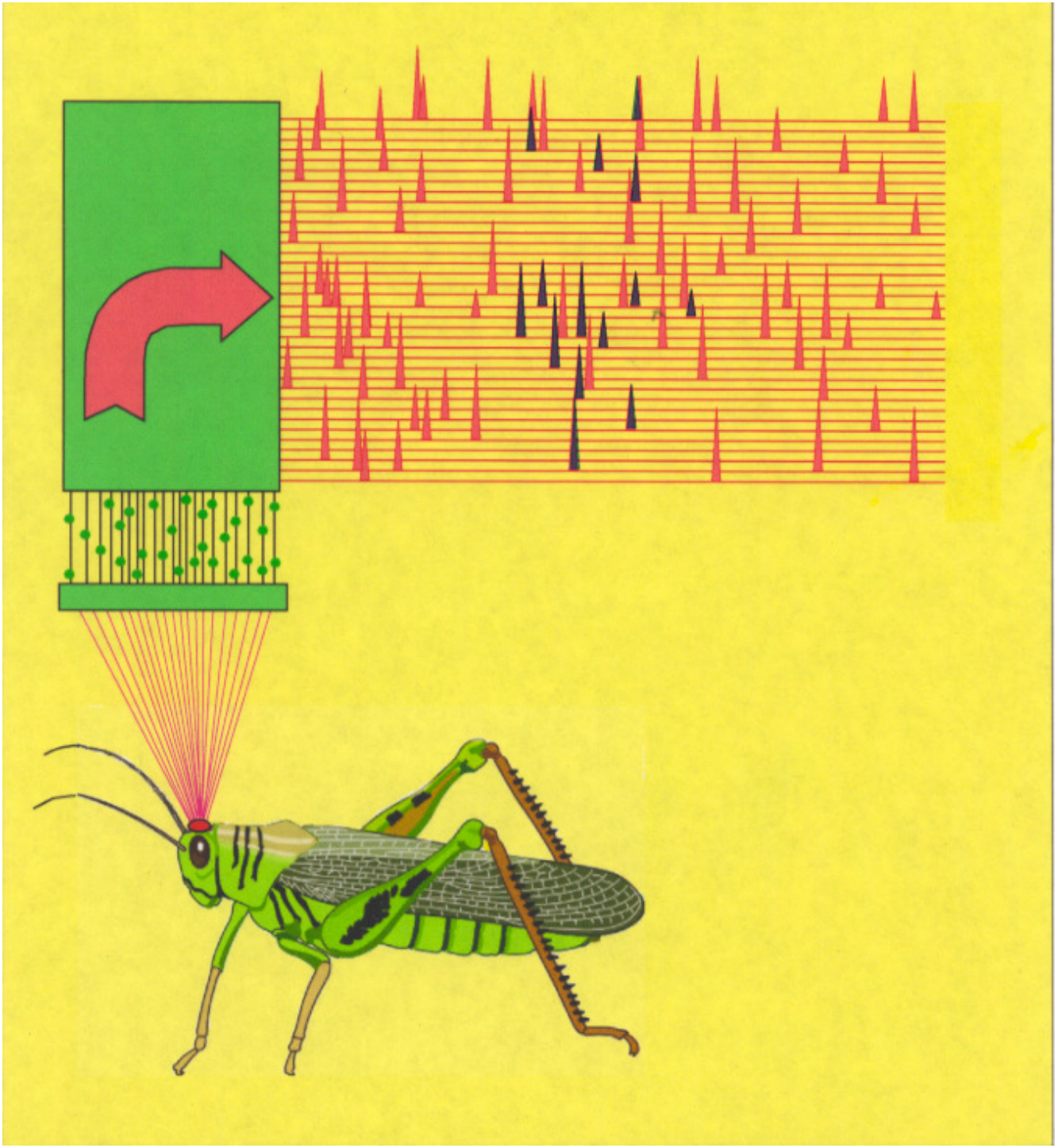
Quantal

Release

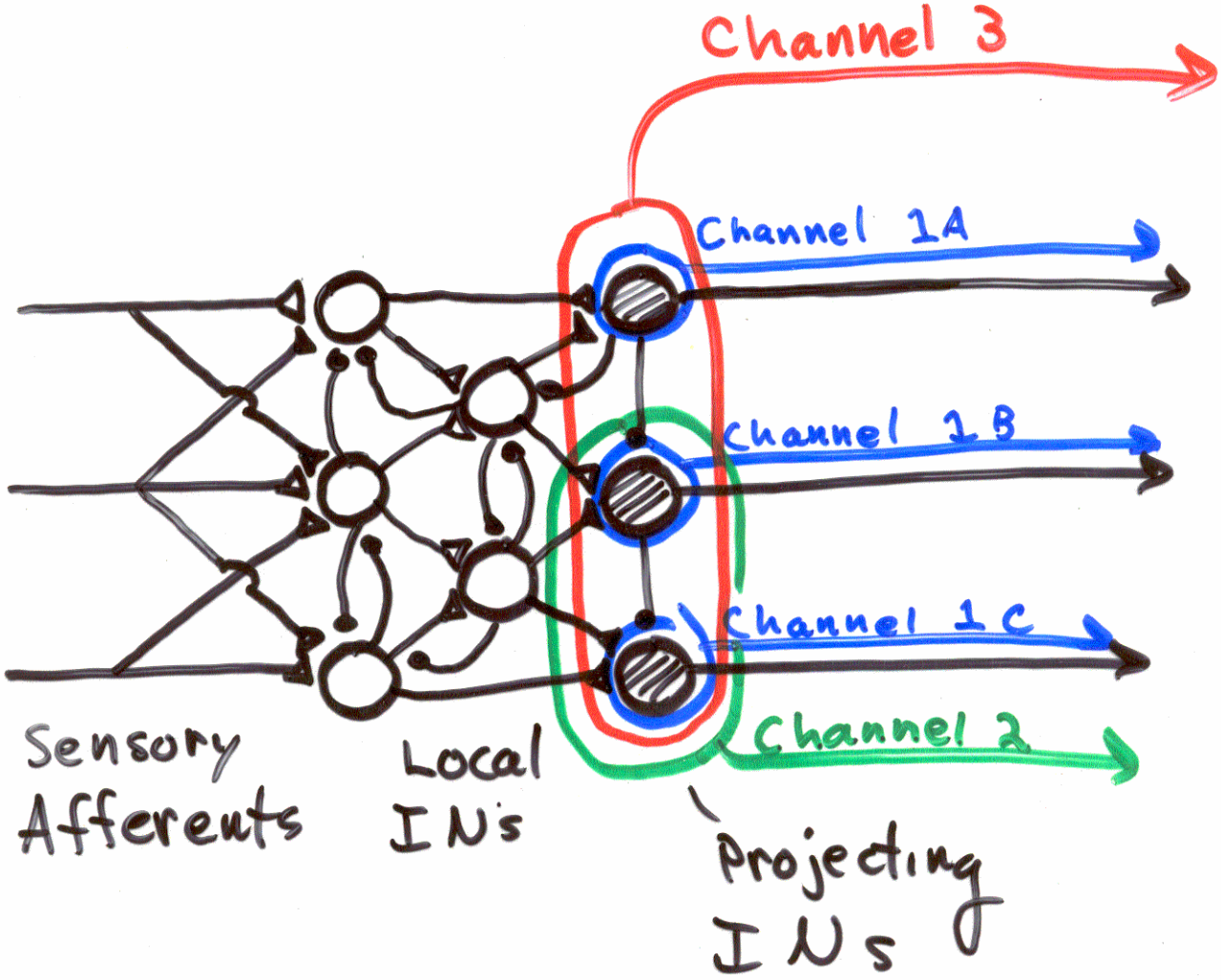
John Miller:

What is the mapping between the functional architecture and the biological architecture? E.g.:

- Is Info theory an appropriate framework for the analysis of neural systems? If so:
  - What is the correlate of an ***information channel*** within a nervous system?
  - What is the nature of the ***neural code***?
  - Is information multiplexed over the channels?



From Miller


Channel 3
Channel 1A
Channel 1B
Channel 1C
Channel 2
Sensory Afferents
Local INs
Projecting INs

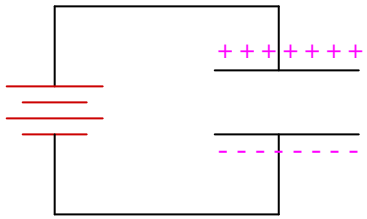
From Miller

Thus I believe treating neuronal action potentials as single "on/off" values or as traditional "bits" ignores most of the information content in the AP. Distribution of information from a single AP occurs over a number of sites and are inherently connected at the second level of abstraction.

What does this resemble?

Quantum Computing

Classical bit

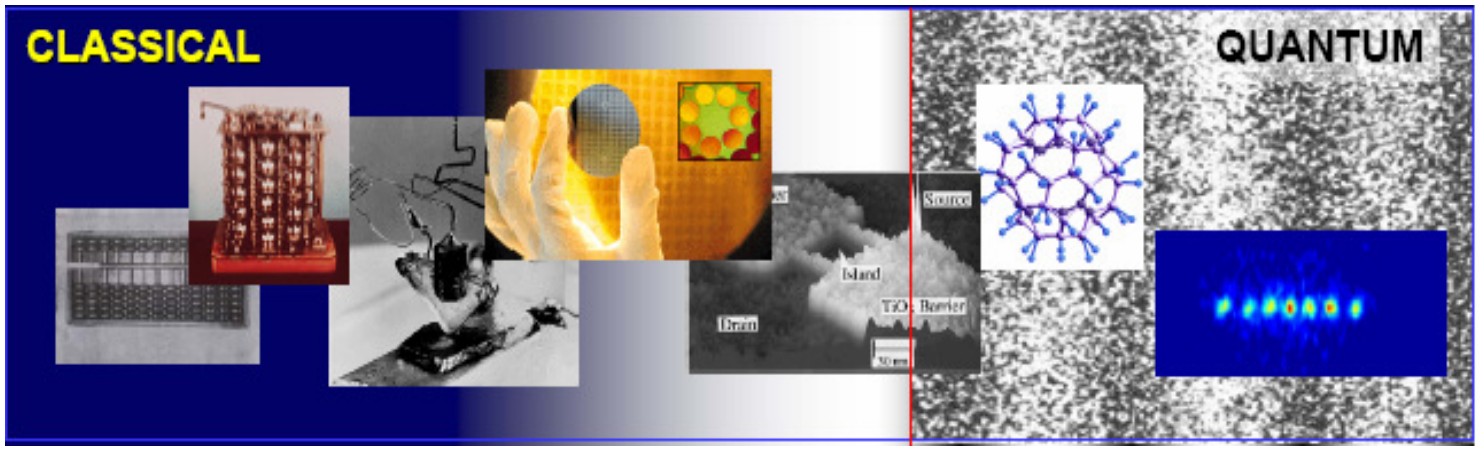


Values 0 or 1

Quantum bit (or "qubit")

Information as state of a two-level quantum system

Values $|0\rangle, |1\rangle$ or Superposition: $\alpha|0\rangle + \beta|1\rangle$



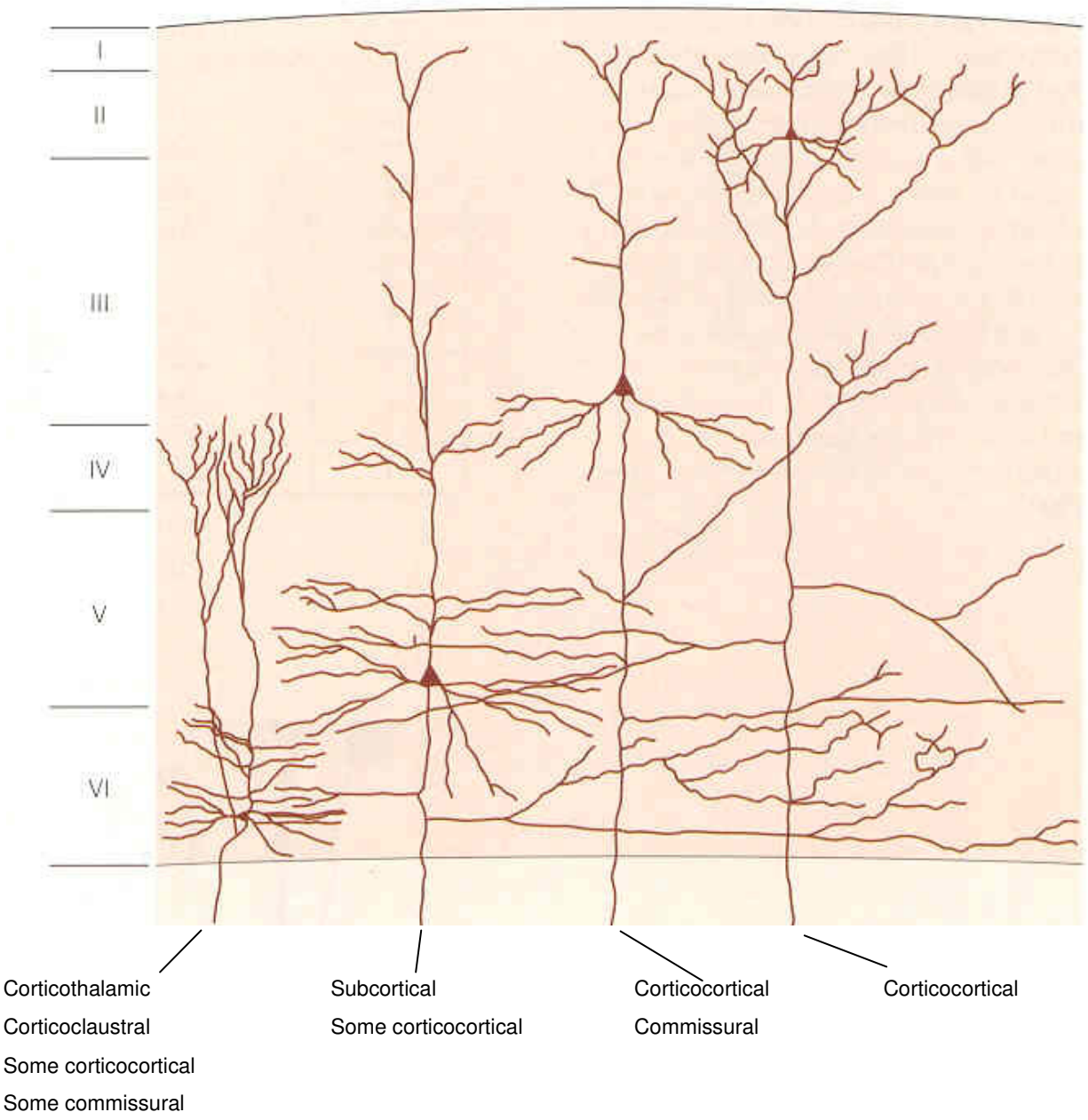
Prediction: a quantum computer can perform computations that no conventional computer ever could.

Courtesy of *NANO*

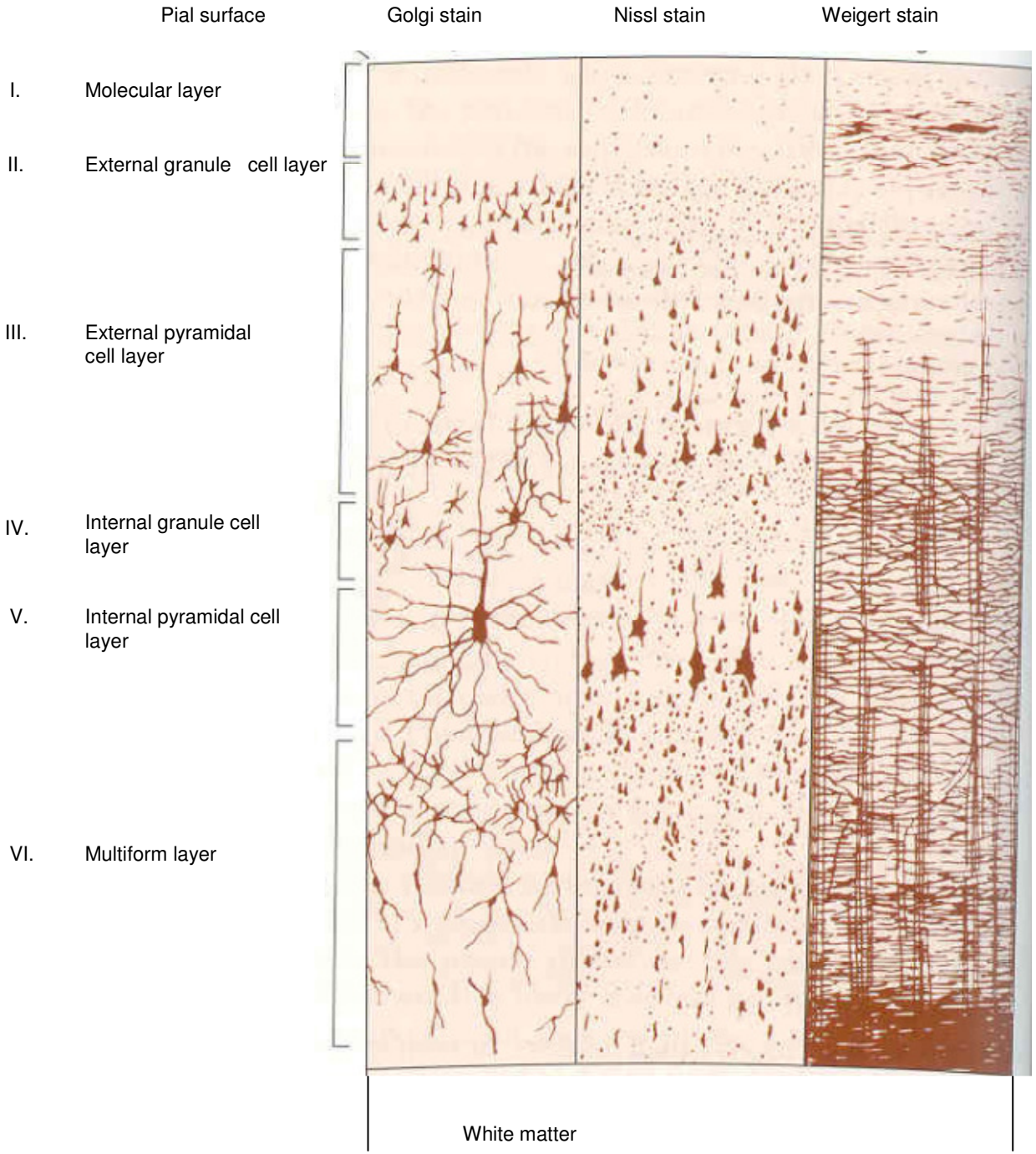
I believe at the second level of abstraction biological information processing and quantum information processing are similar and these "entangled systems" can interact with each other

But, why is this interesting in terms of AI?

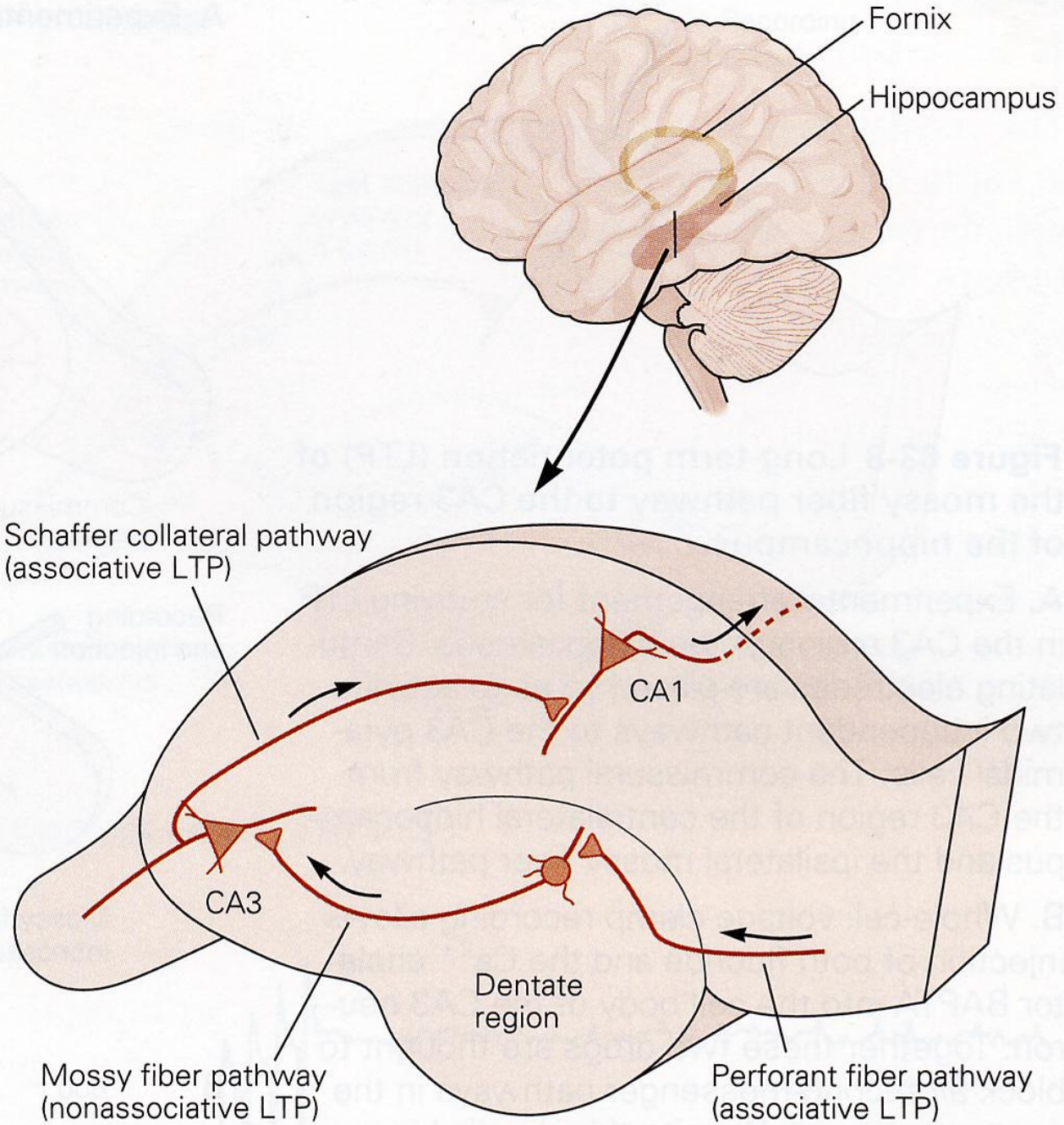
Because of what I think is the THIRD level of abstraction - Intuition



Neurons in different layers of the neocortex project to different parts of the brain. Projections to other parts of the neocortex, the so-called corticocortical or associational connections, arise primarily from neurons in layers II and III. Projections to subcortical regions arise mainly form layers V and VI (From Kandell)



The neurons of the cerebral cortex are arranged in distinctive layers. The appearance of the cortex depends on what is used to stain it. The Golgi stain reveals neuronal cell bodies and dendritic trees. The Nissl method shows cell bodies and proximal dendrites. A Weigert stain for myelinated fibers reveals the pattern of axonal distribution (From Kandell).

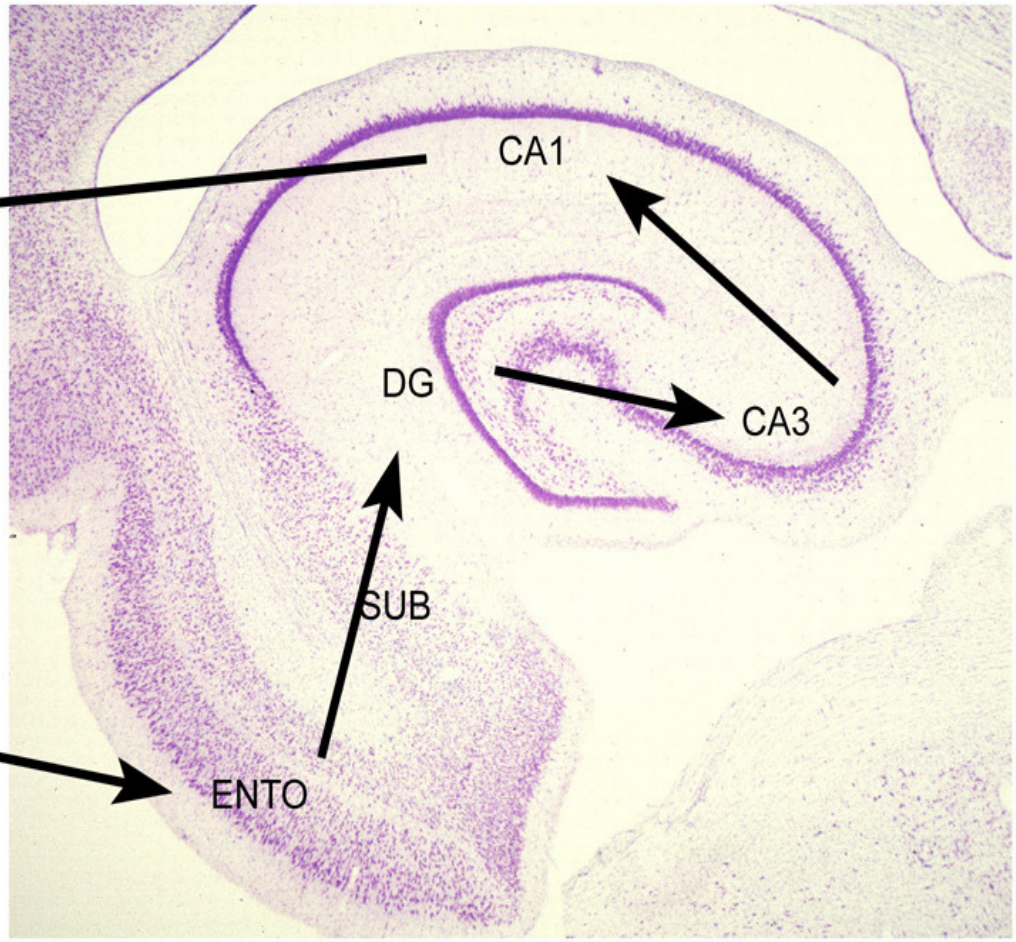

Fornix
Hippocampus
Schaffer collateral pathway
(associative LTP)
CA1
CA3
Dentate
region
Mossy fiber pathway
(nonassociative LTP)
Perforant fiber pathway
(associative LTP)

NEOCORTEX

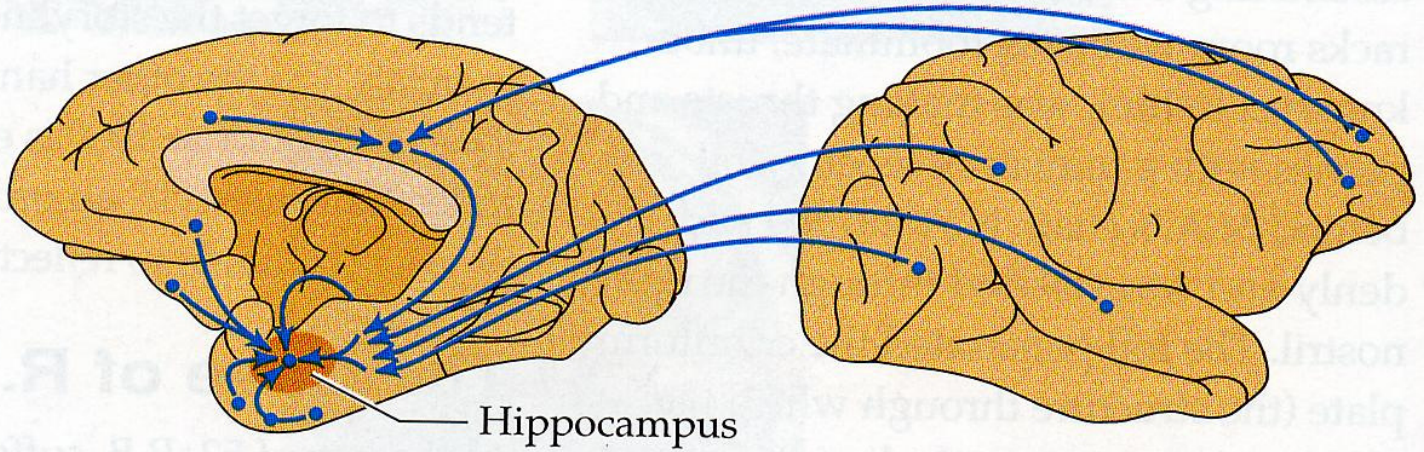
HIPPOCAMPUS

RE-ENCODING FOR LONG-TERM STORAGE

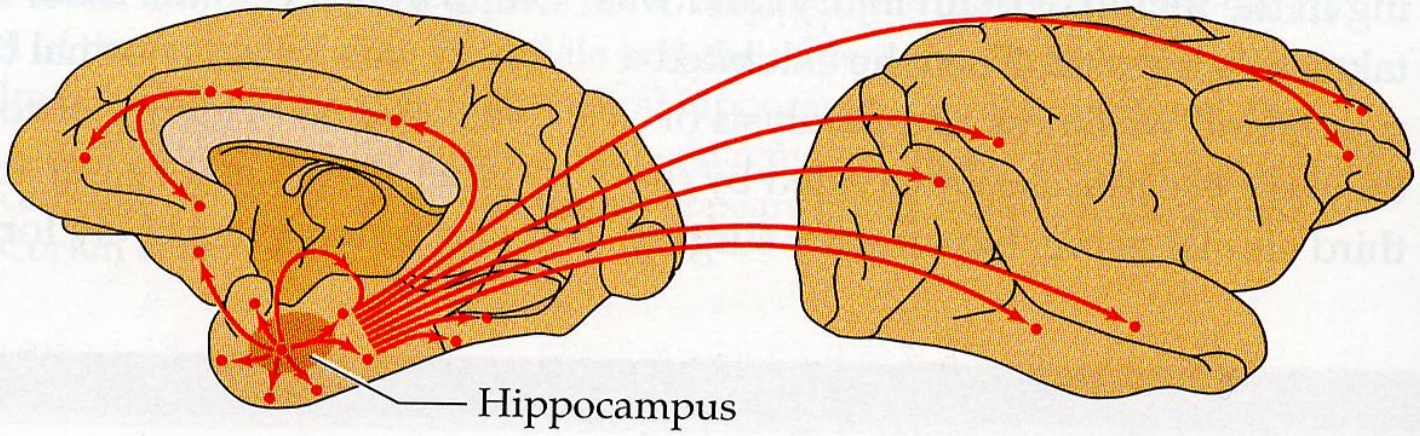
MULTI-MODAL REPRESENTATIONS



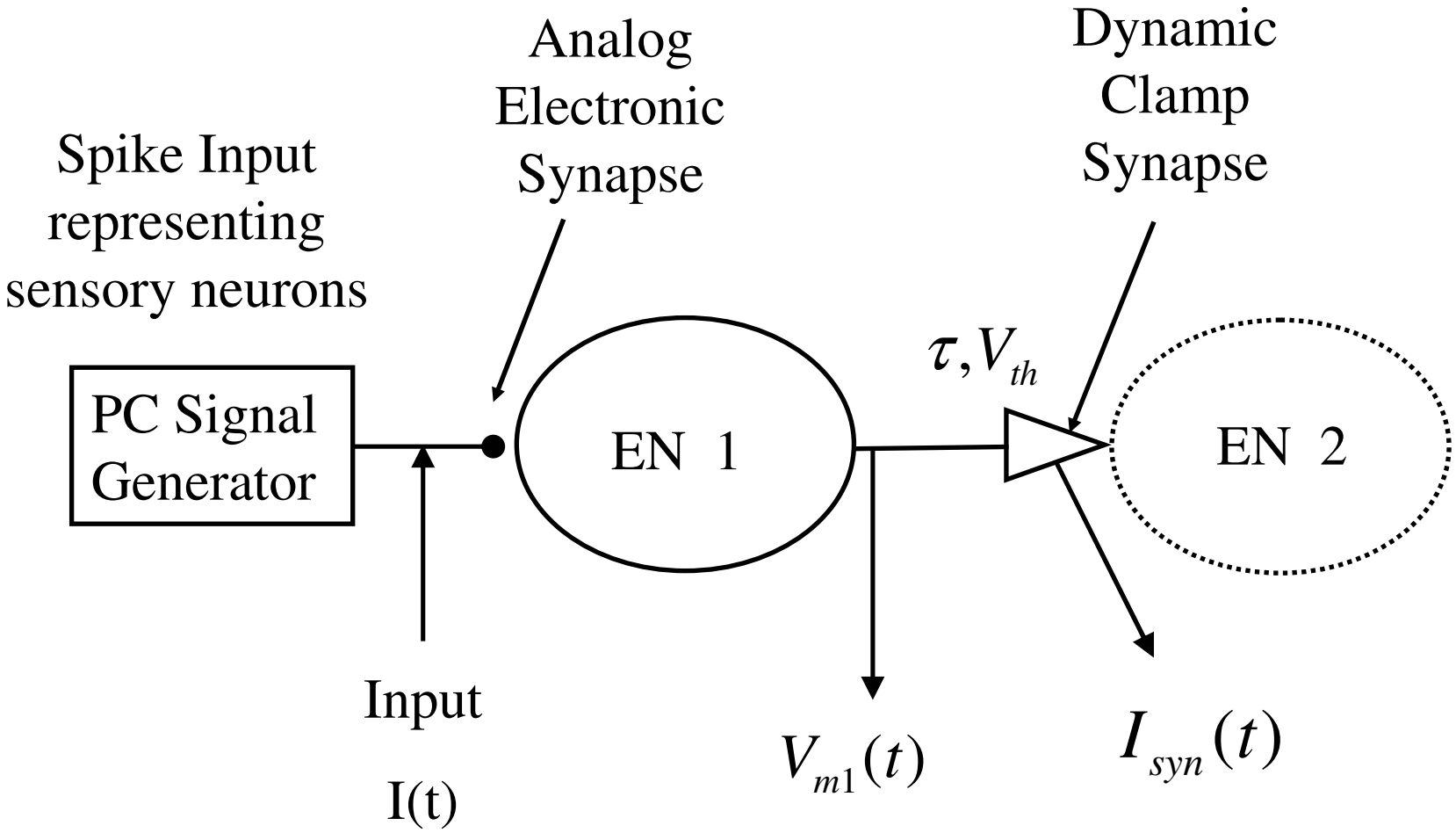
(A) Afferent connections of the hippocampal region



(B) Efferent connections of the hippocampal region

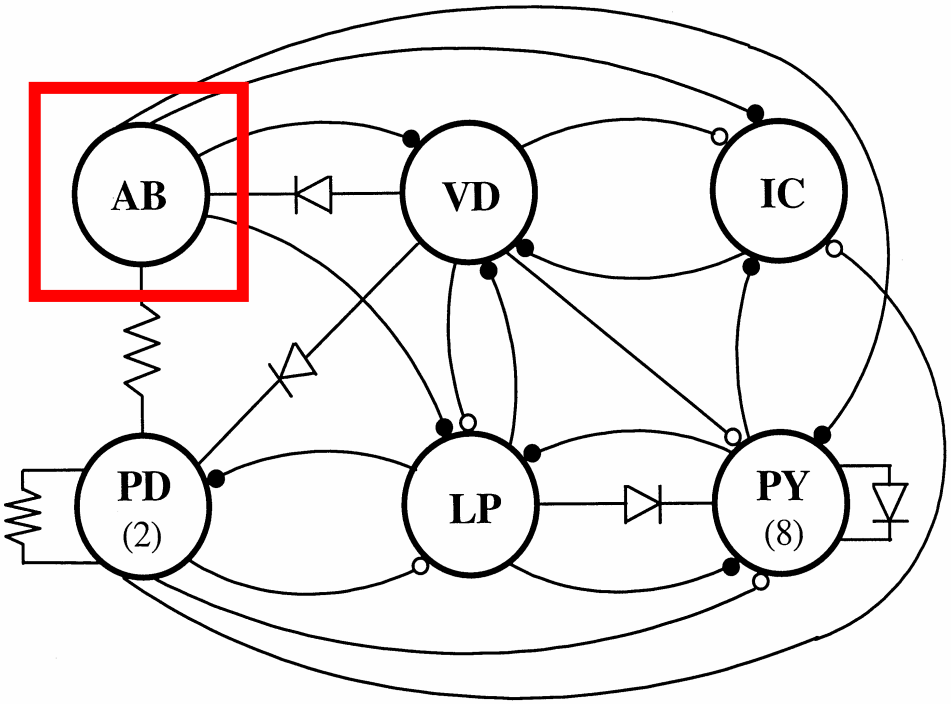


Abarbanel used "channels" of Electronic Neurons (Ens) coupled with analog circuit synapses and computer synapses (dynamic clamp) to explore information transport in neural circuits



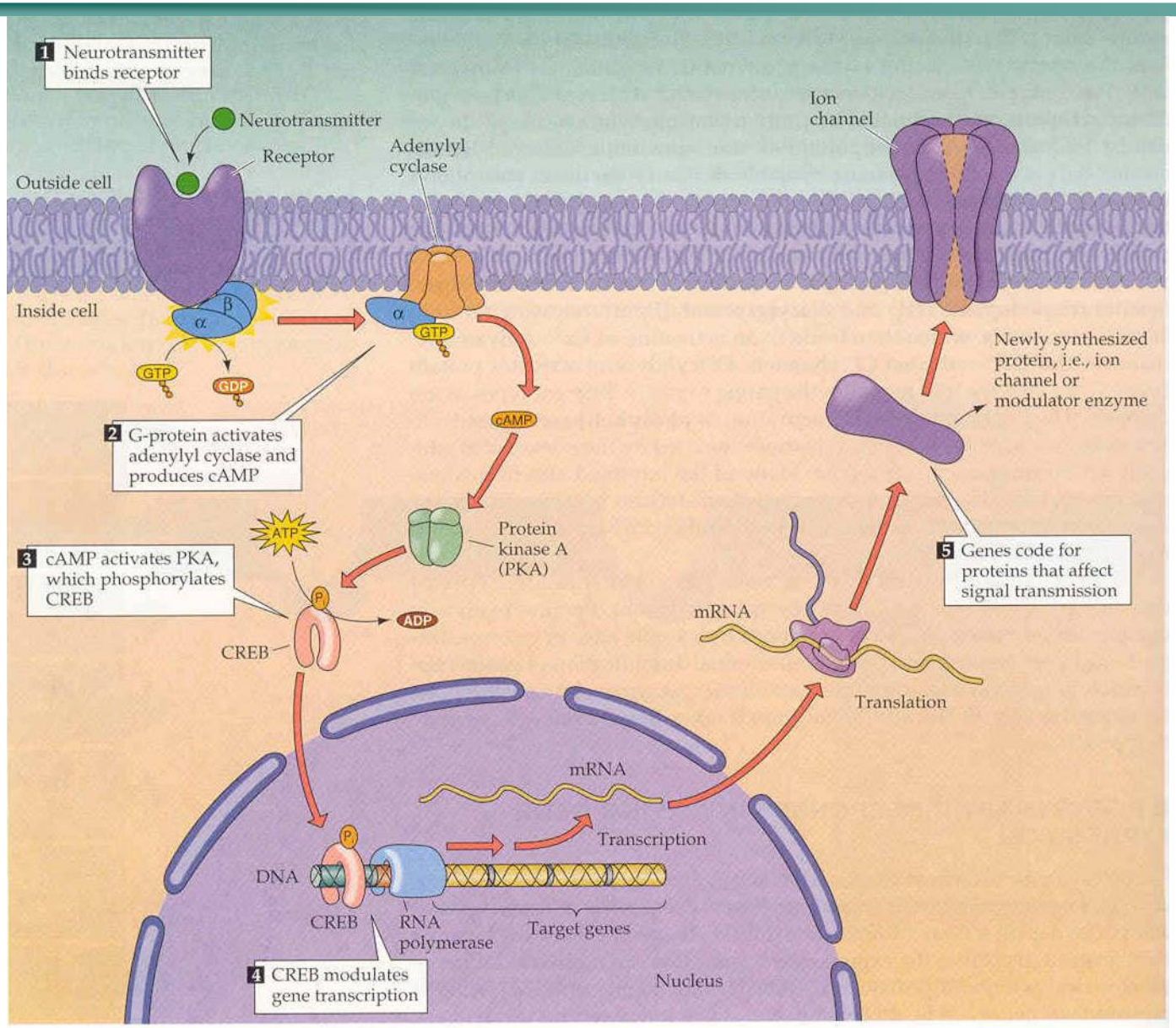
From Abarbanel

Analog circuit ENs quantitatively replaced a biological neuron removed from the Pyloric Central Pattern Generator and restored the natural rhythm of the biological circuit:

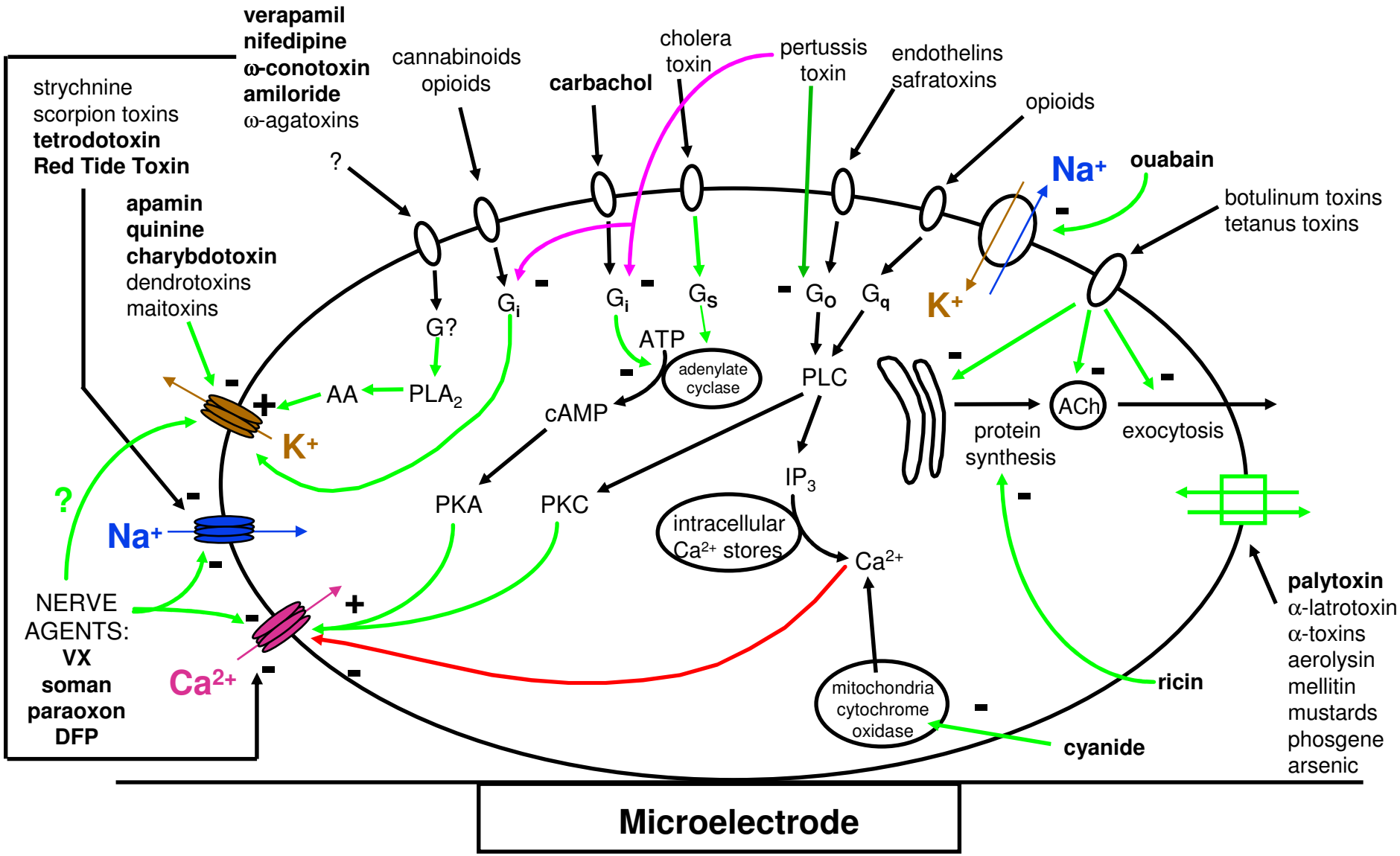


From Abarbanel

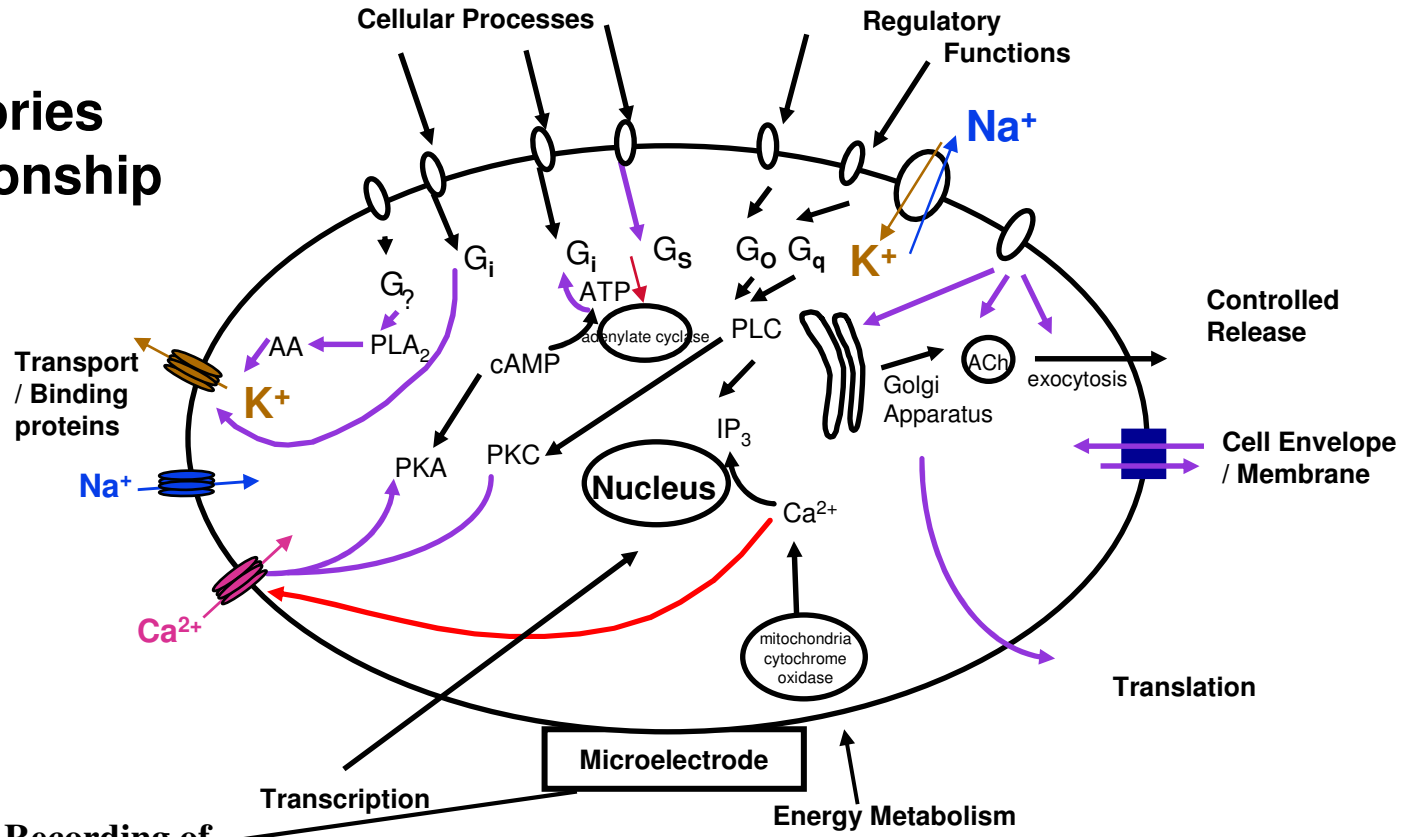
Neurotransmitters can give rise to prolonged postsynaptic charges by modulating gene expression.



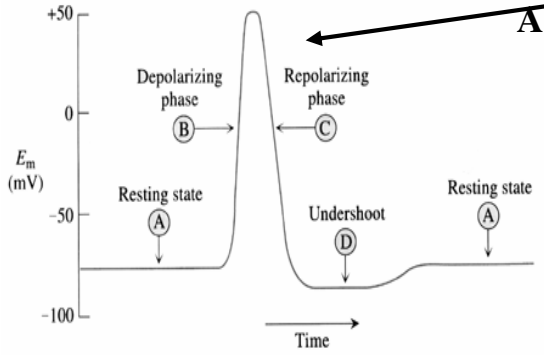
In Vitro to *In Silico* Networks



Function Categories and Their Relationship to Pathways

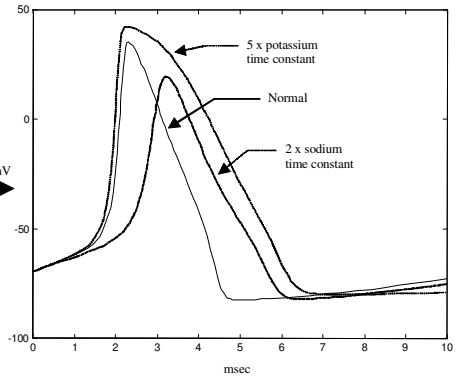


Recording of Action Potentials



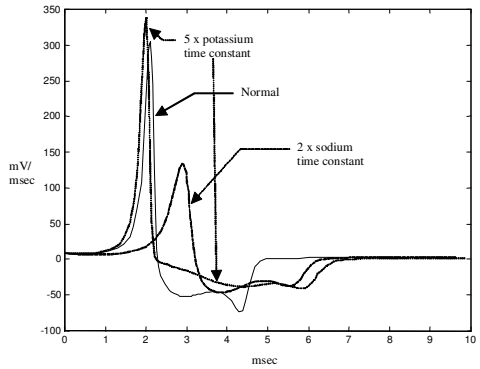
Standard Action Potential Recording

Analysis of AP peak shape changes



a -- Membrane Potential

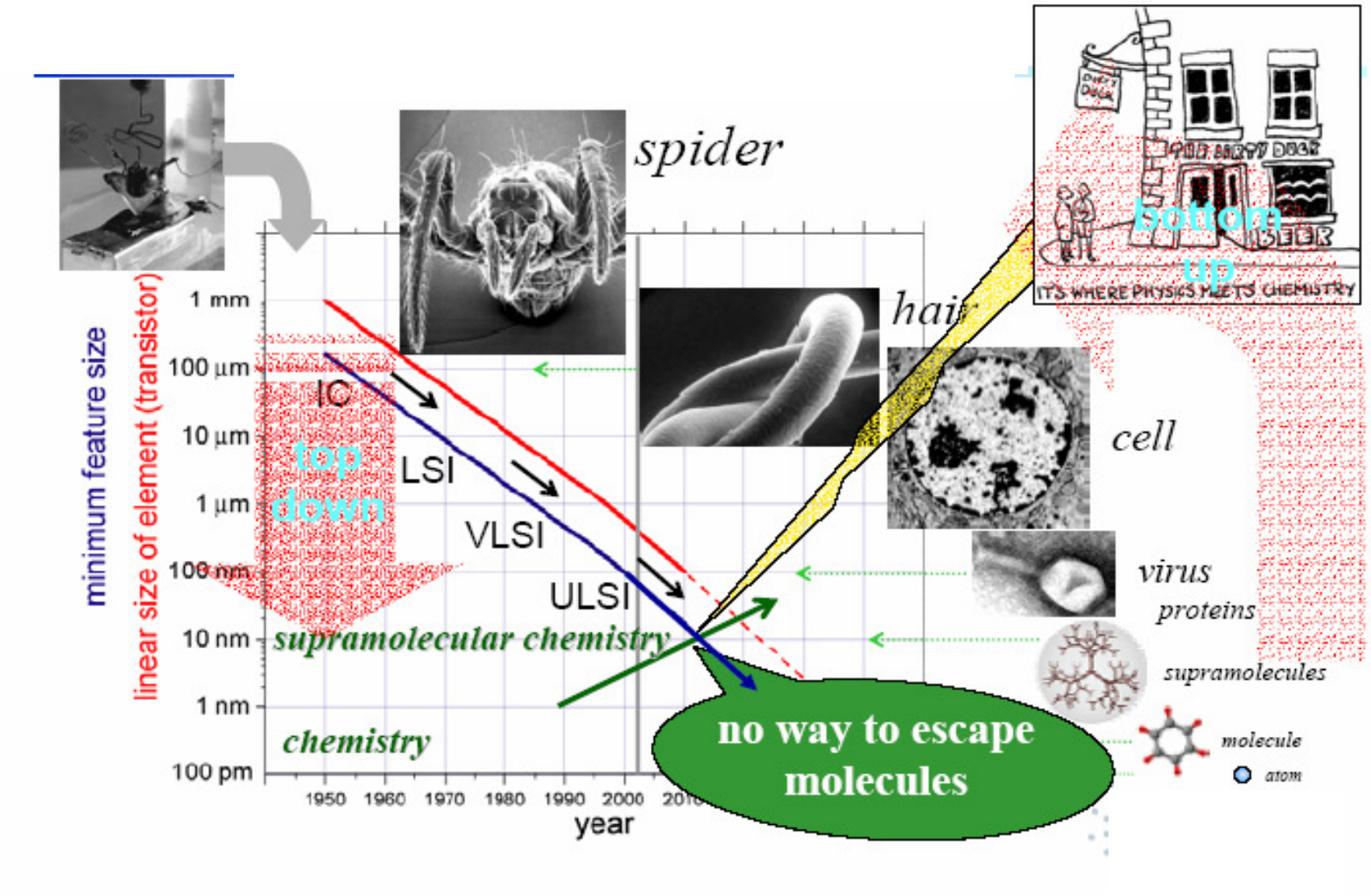
High Seal Resistance



b -- Derivative of Membrane Potential

Medium Seal Resistance

Integrated Circuit scaling

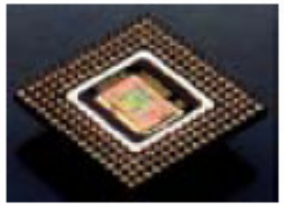


Courtesy of *NANO*

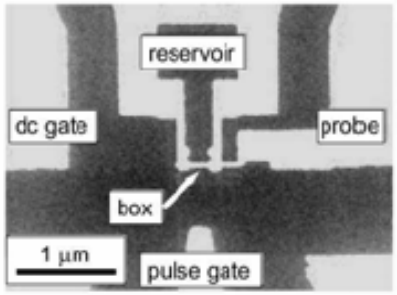
Future Nanotechnologies for Electronics?

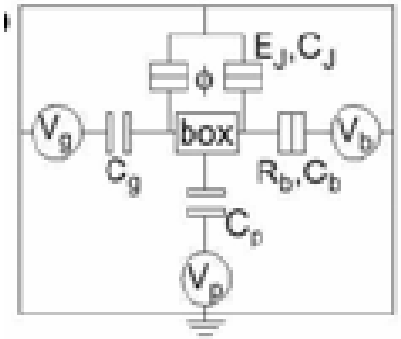
Mainstream electronics

top-down
silicon



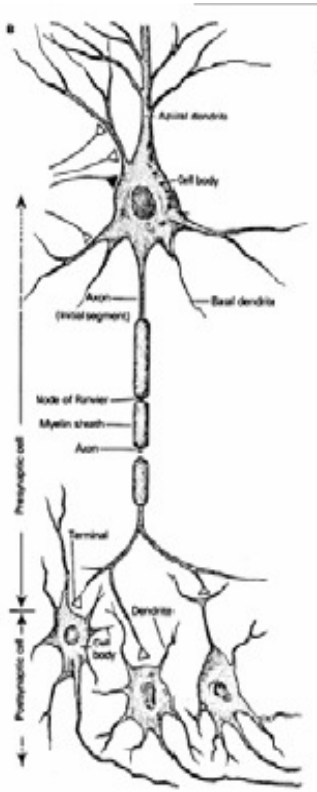
Quantum Computer





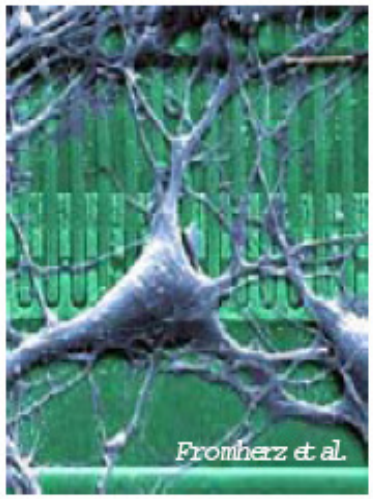
: tunnel junction
: capacitor

Biological Computation



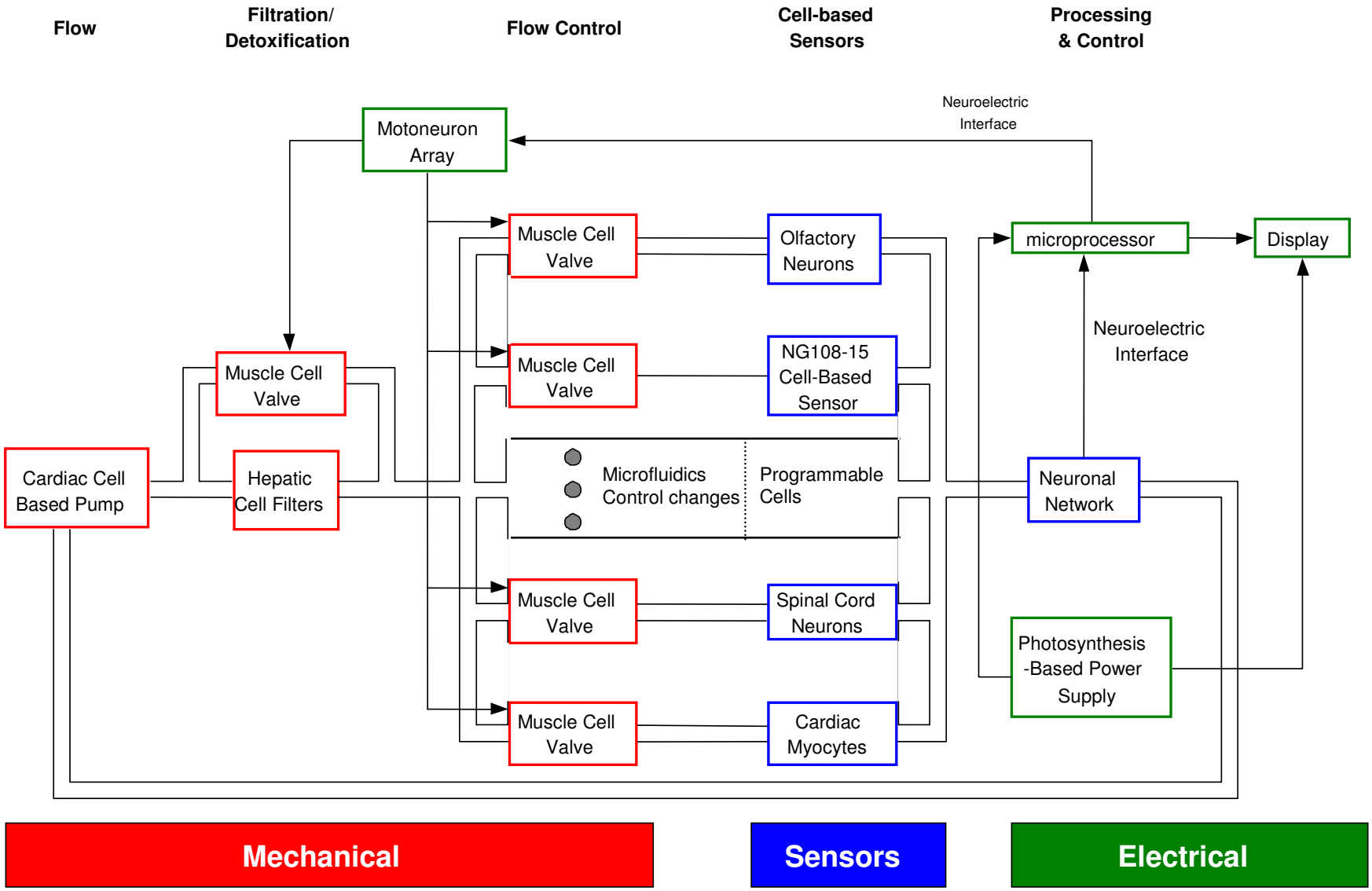
Brain, neural networks, and computation

J. J. Hopfield

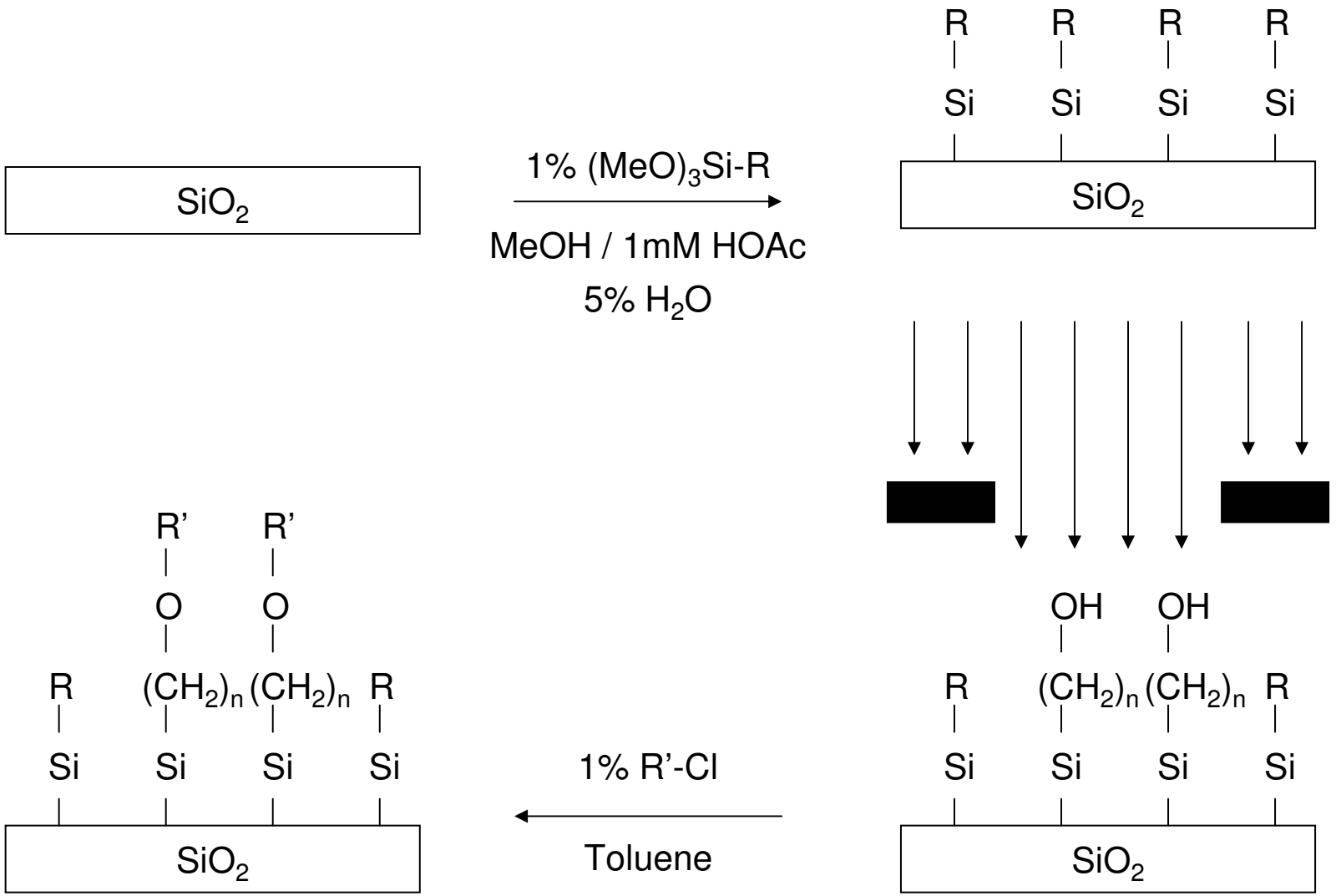


Courtesy of *NANO*

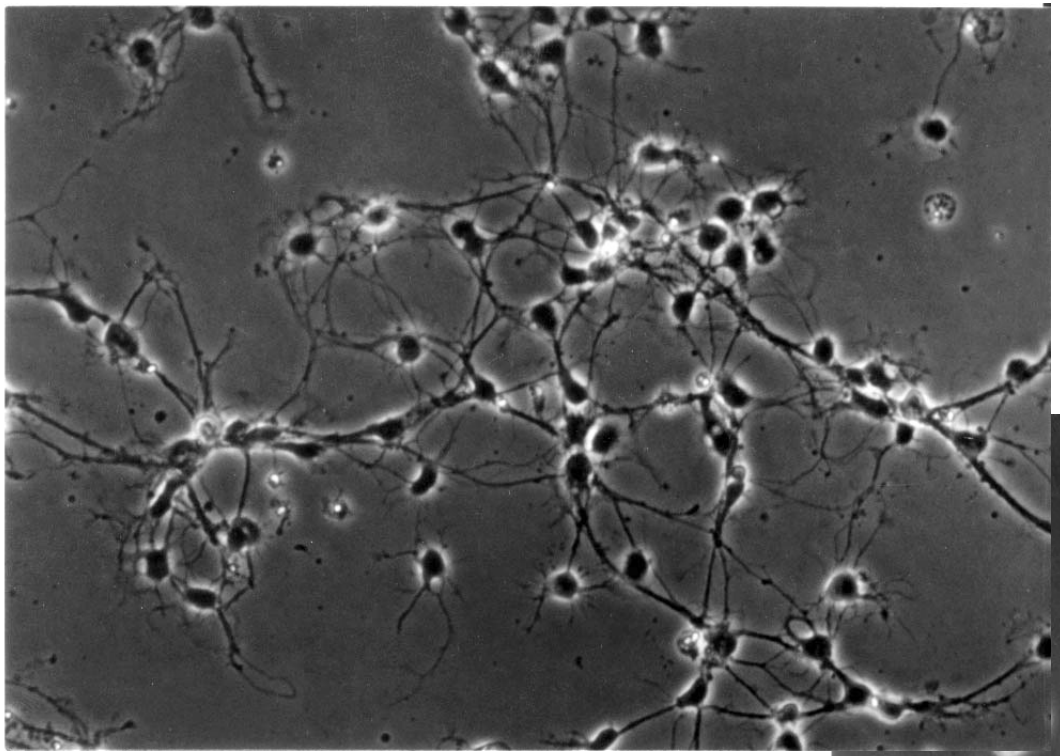
Integrated Bio-Systems



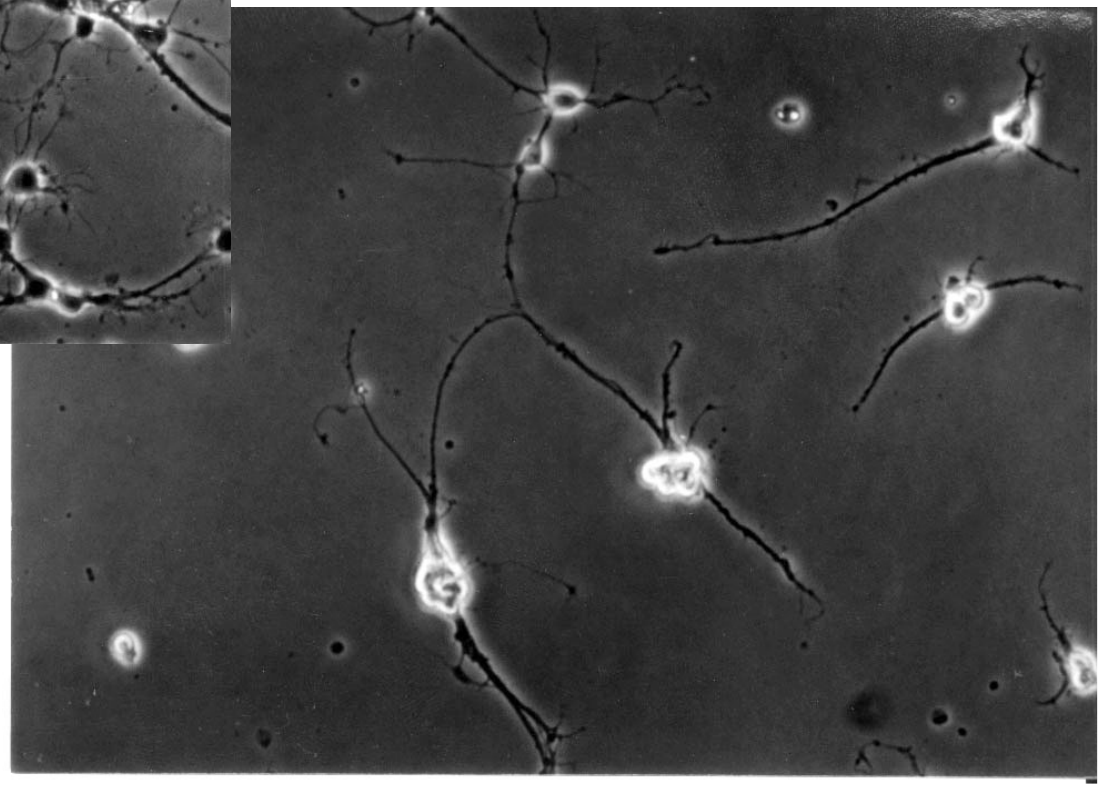
Fabrication of Coplanar SAMs



7 Day Old E18 Rat Hippocampal Neurons in Serum-Free Media on Cytophilic and Cytophobic Surfaces

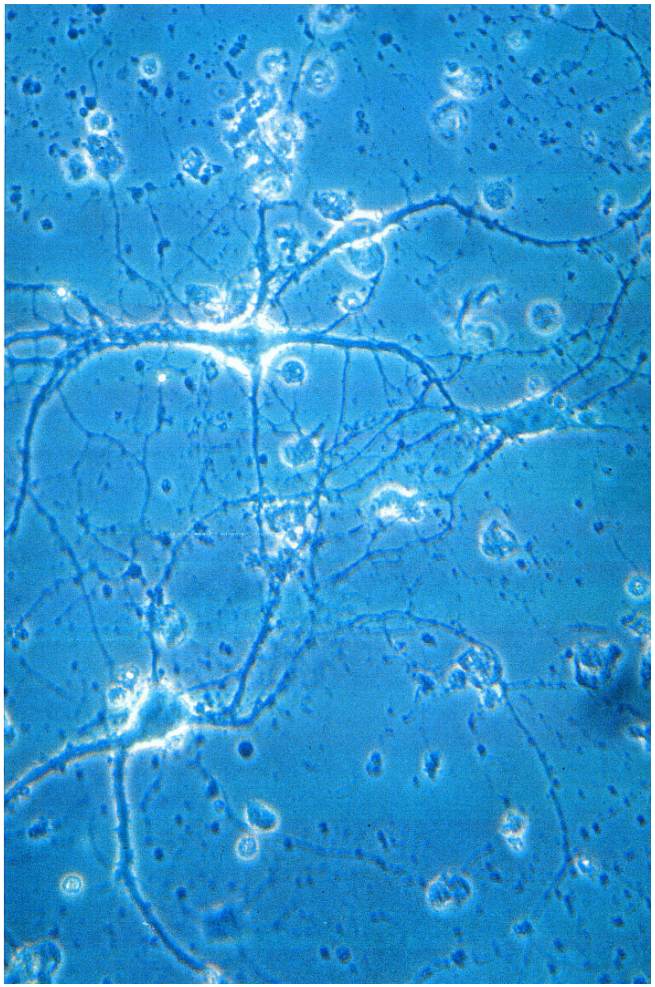


DETA – an amine containing silane SAM

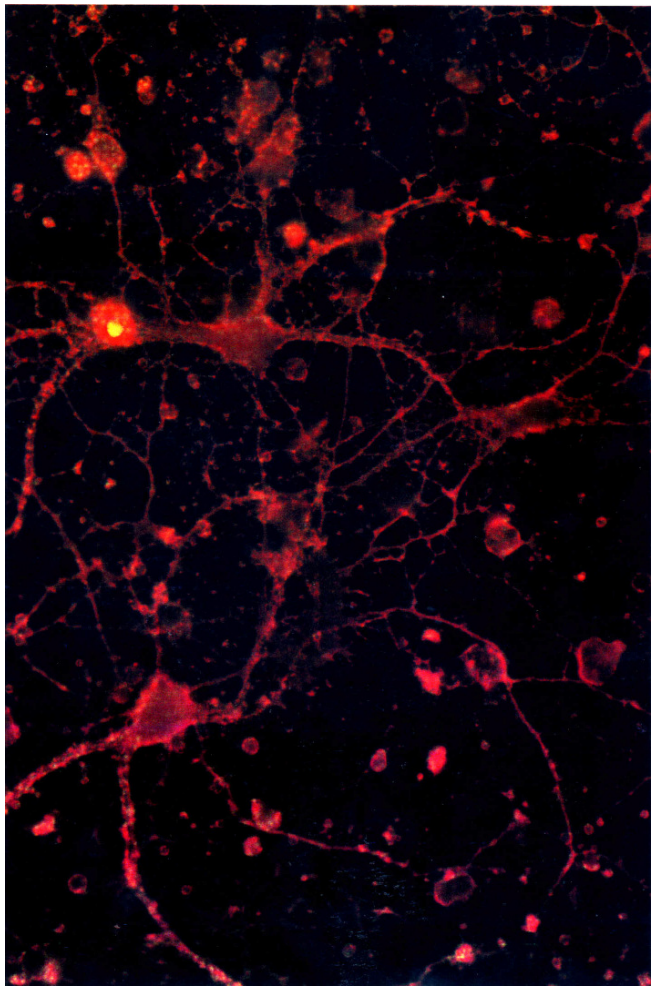


15F – a flourinated silane SAM

Five Week Old Hippocampal Cultures from E18 Rats in Serum free Media on DETA - an Amine Containing Silane

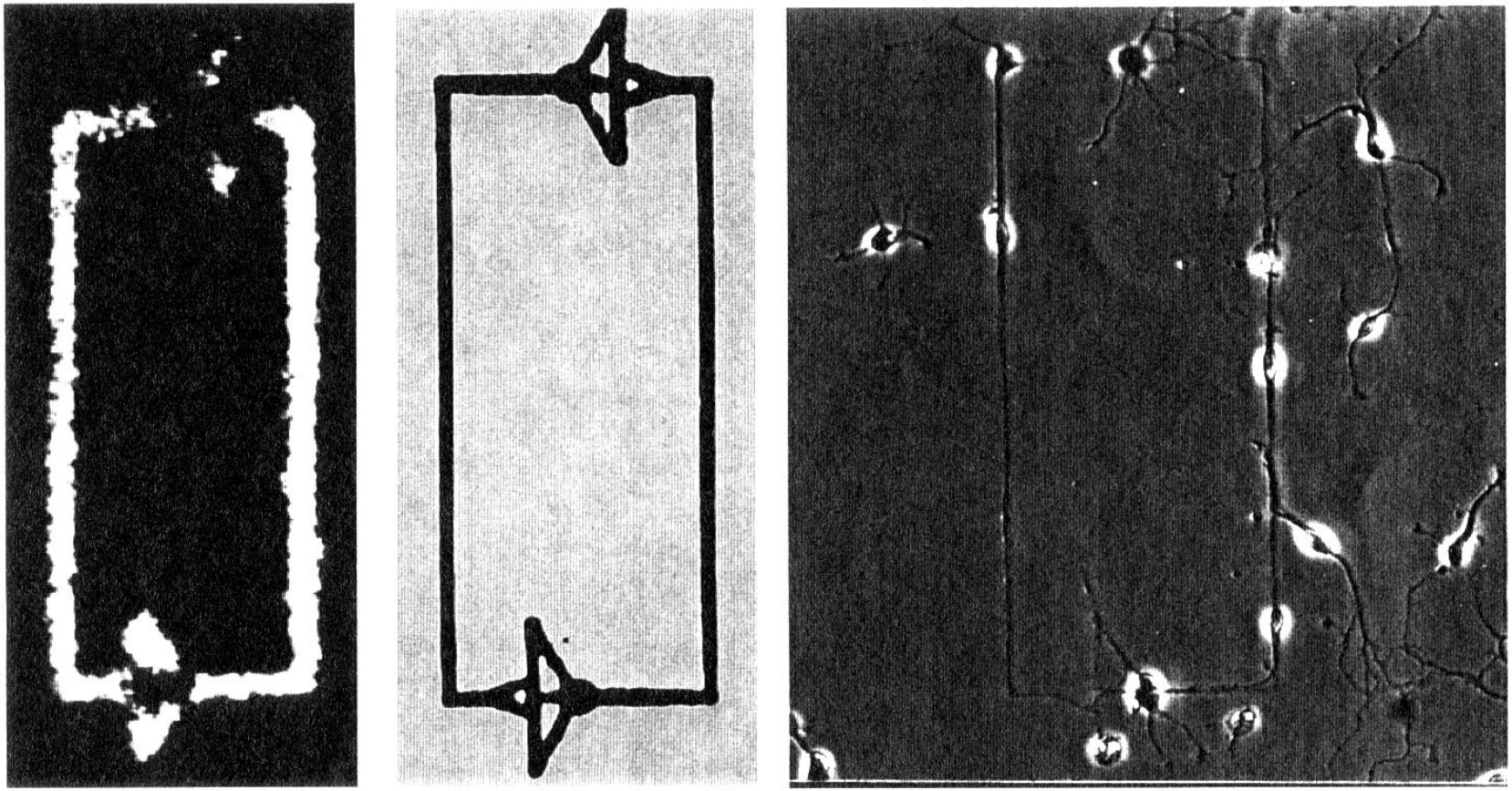


Phase Contrast



Nueron Specific Stain

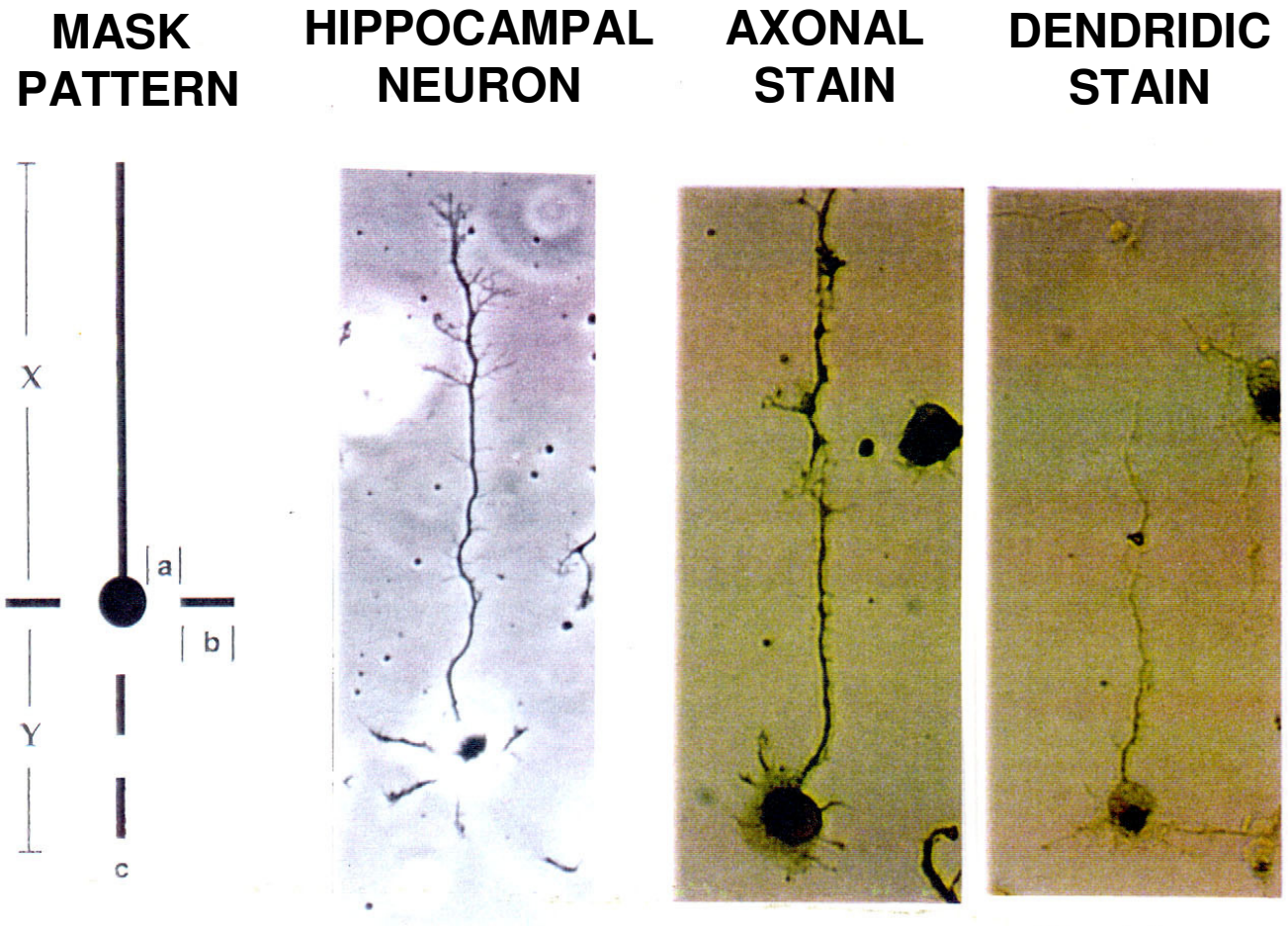
Neuronal Circuit Pattern Utilizing Hippocampal E18 Neurons in Serum- Free Media After 7 Days in Culture



XPS Pd Image Pattern Cells obeying pattern region

Ravenscroft, M.S., Bateman, K.E., Shaffer, K.M., Schessler, H.M., Jung, D.R., Schneider, T.W., Montgomery, C.B., Custer, T.L., Schaffner, A.E., Liu, Q.Y., Li, Y.X., Barker, J.L.and Hickman, J.J. (1998) developmental neurobiology implications from fabrication and analysis of hippocampal neuronal networks on patterned silane-modified surfaces. *J. Amer. Chem. Soc.* 120, 12169-12177

Polarity Determination Using Only Geometry and Cytophilic Surface



Stenger, D.A., Hickman, J.J., Bateman, K.E., Ravenscroft, M.S., Ma, W., Pancrazio, J.J., Shaffer, K., Schaffner, A.E., Cribbs, D.H. and Cotman. C.W. (1998). Microlithographic determination of axonal/dendritic polarity in cultured hippocampal neurons. *J. Neuroscience Methods*. 82, 167-173.

Intracellular Recording

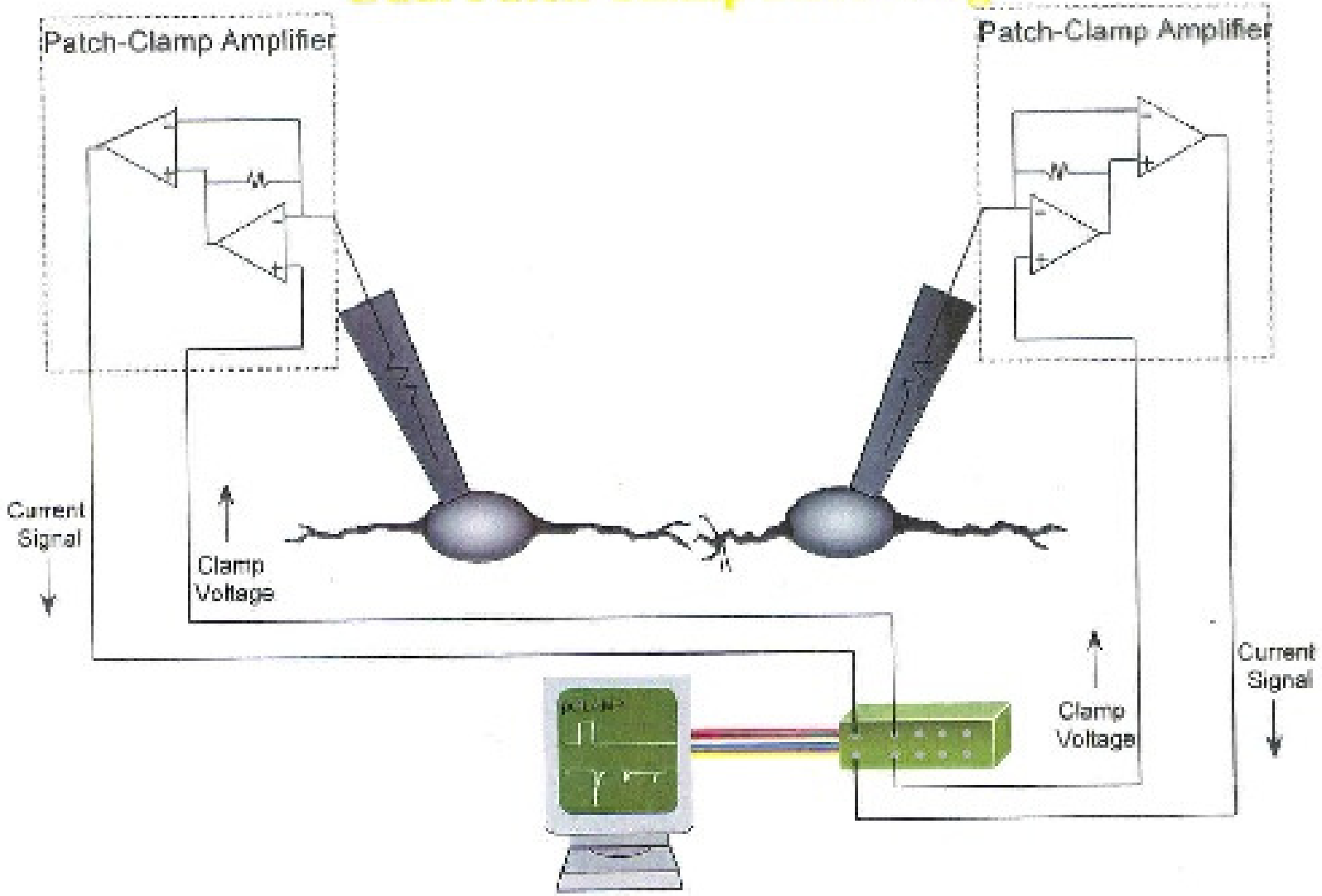
Classical recording (Patch Clamp) :

- two electrodes
- one in the cell
- one reference in the bath

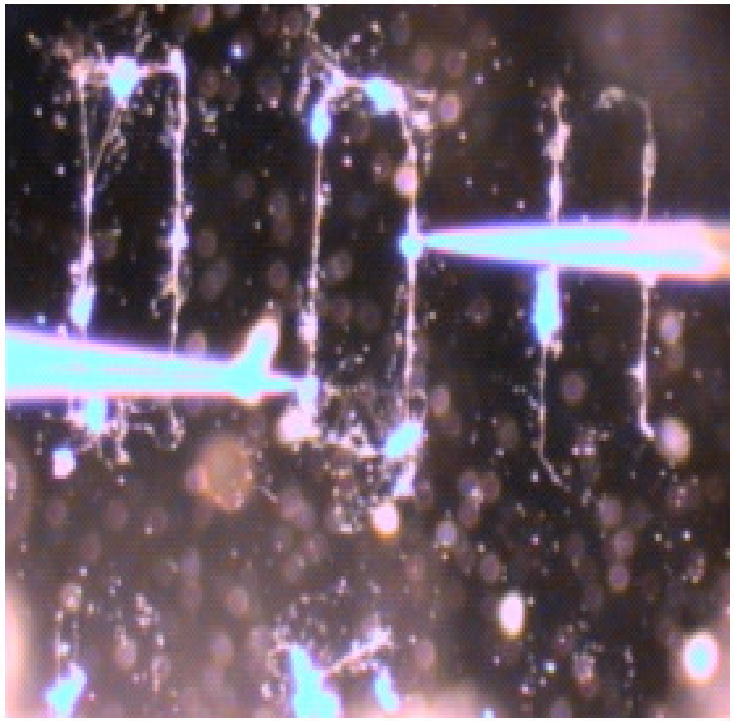
Result : Membrane potential

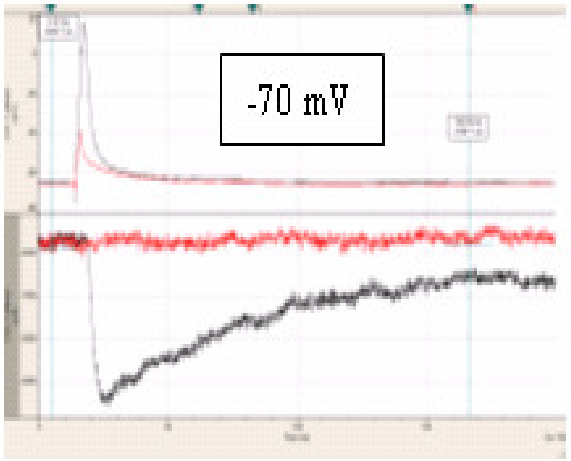
http://www.multichannelsystems.com/heartbeat.pdf

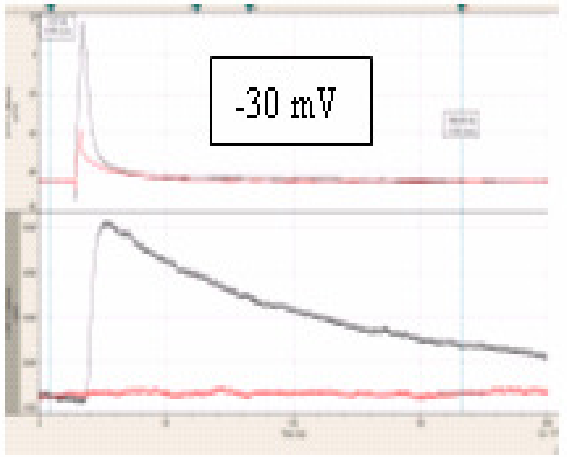
Dual Patch Clamp Recording

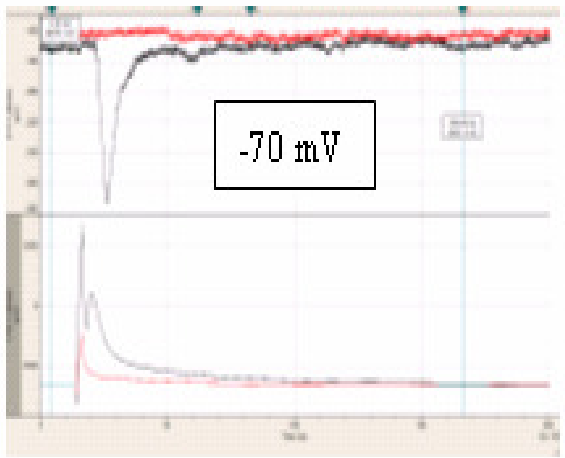


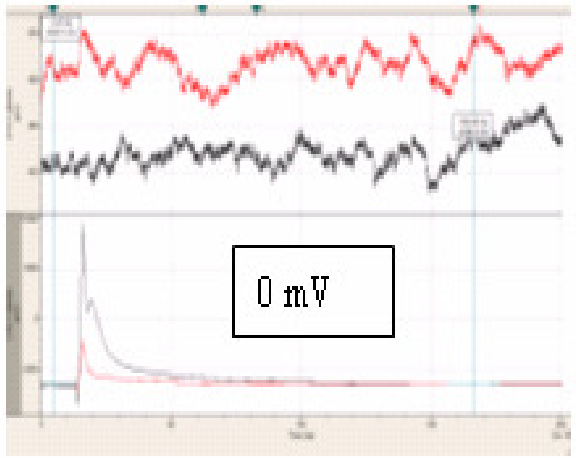
Recordings from excitatory/inhibitory circuits on simple patterns in serum free media



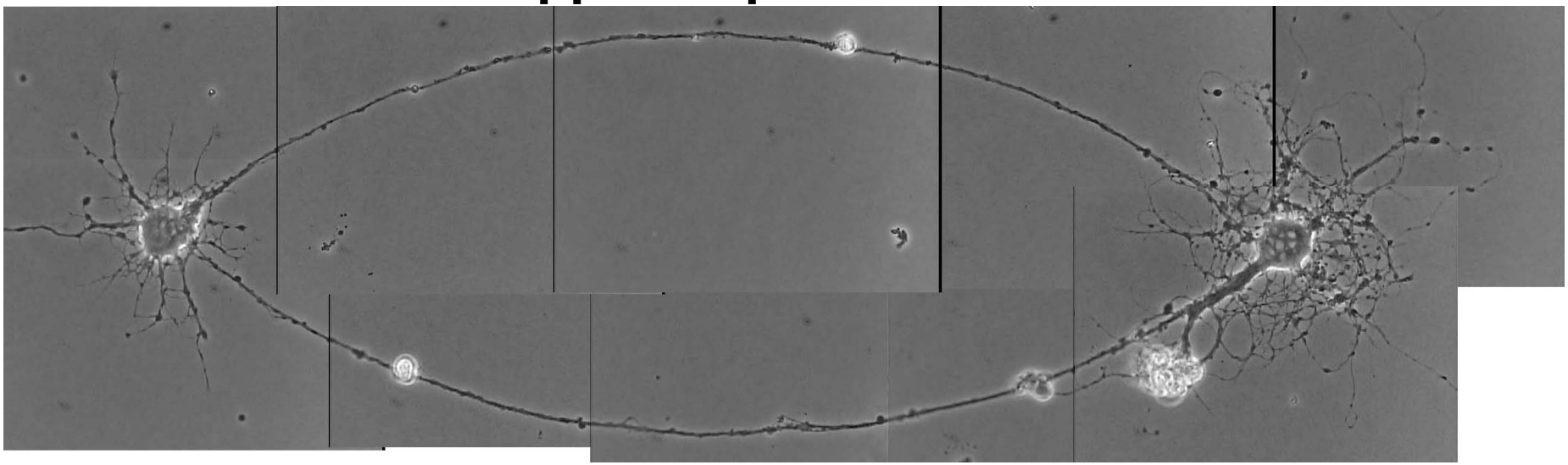


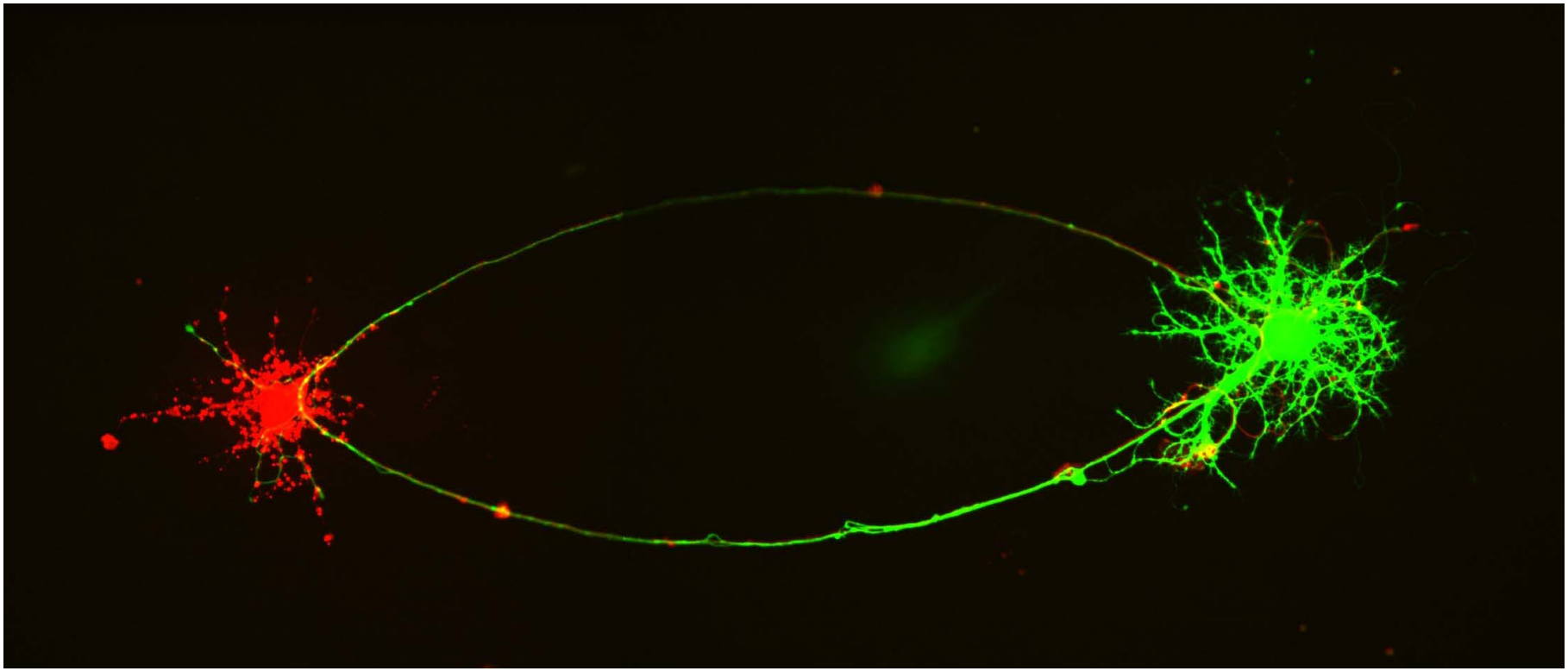


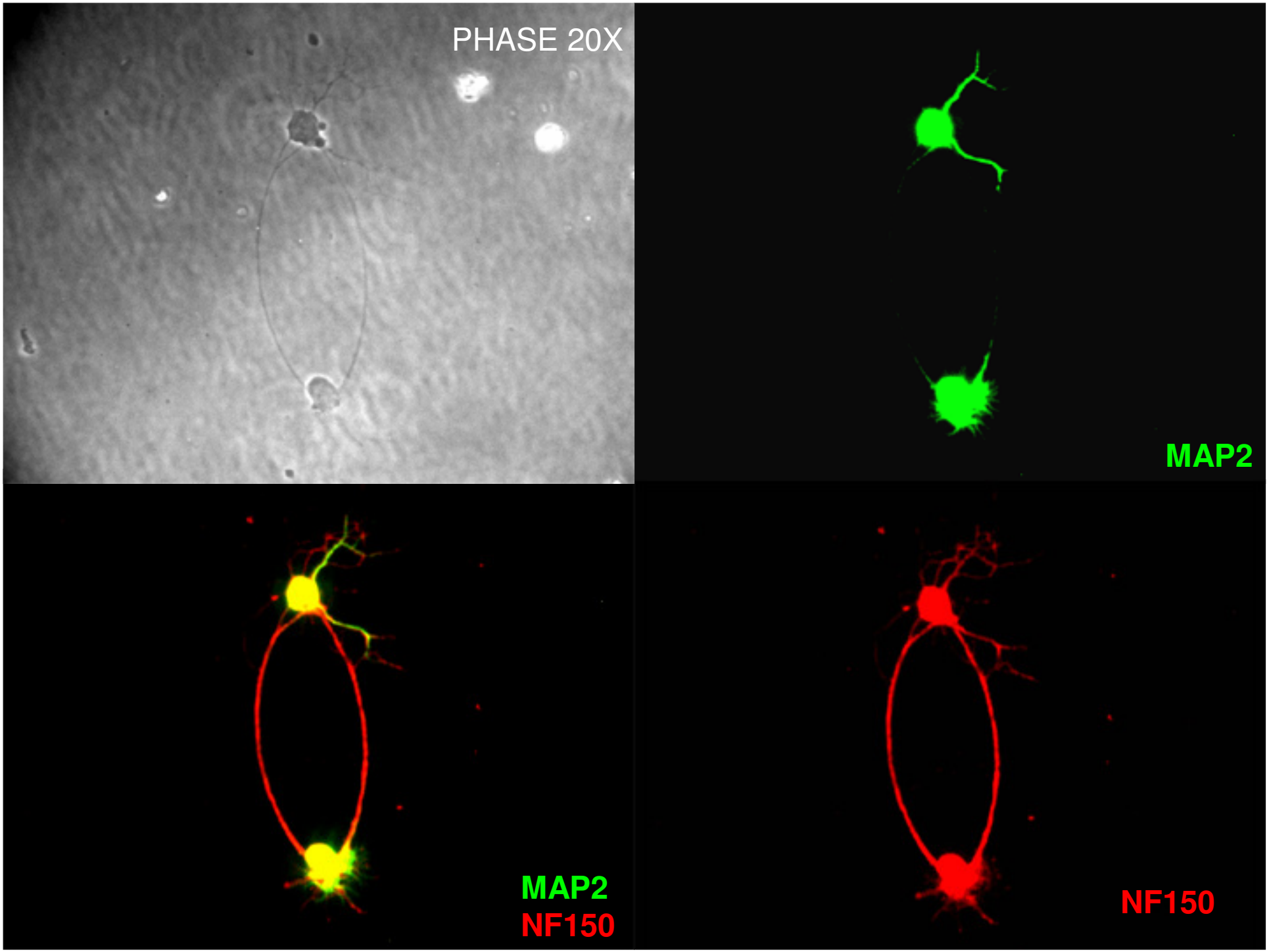


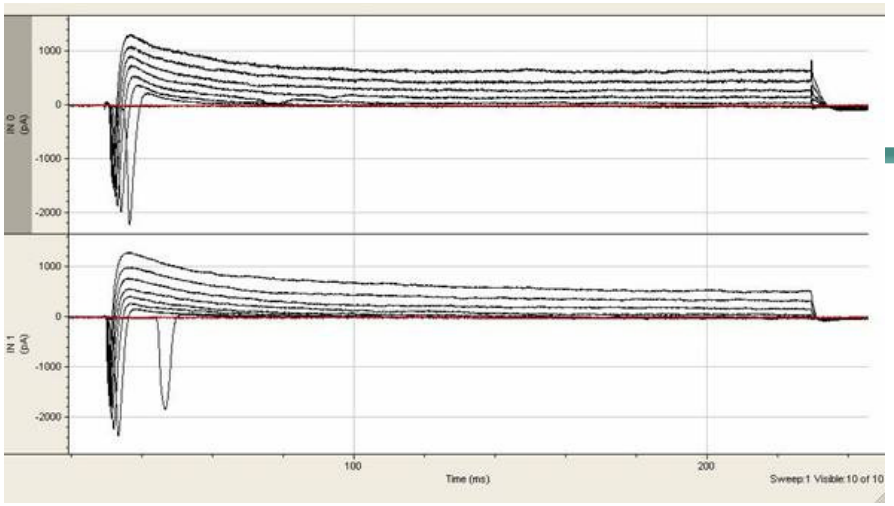


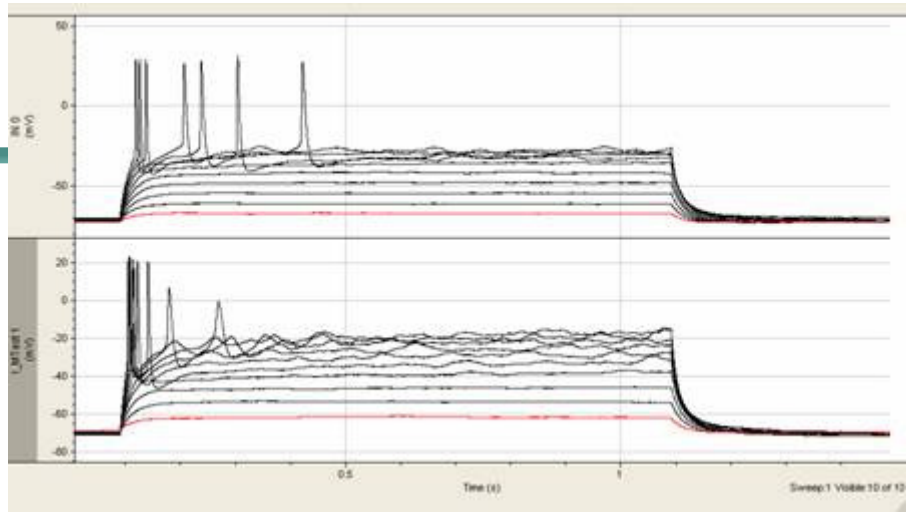
Advanced Hippocampal Two-Cell Networks

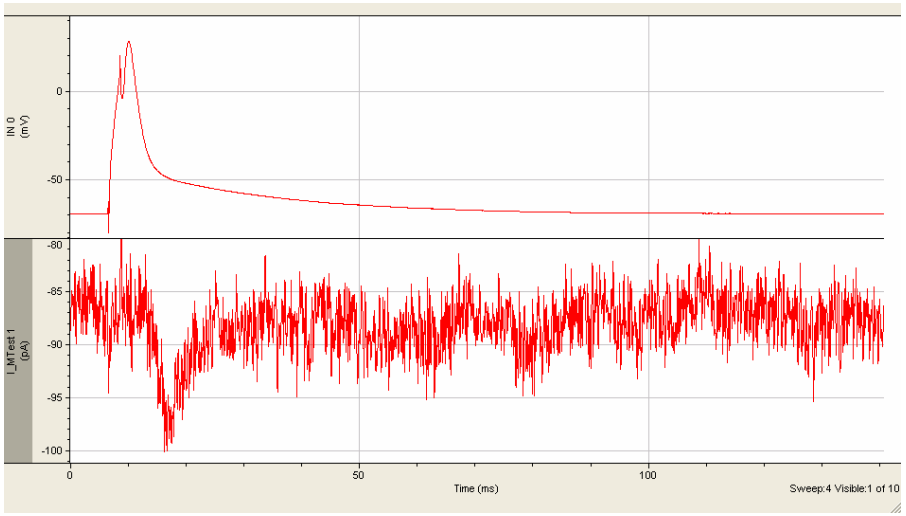


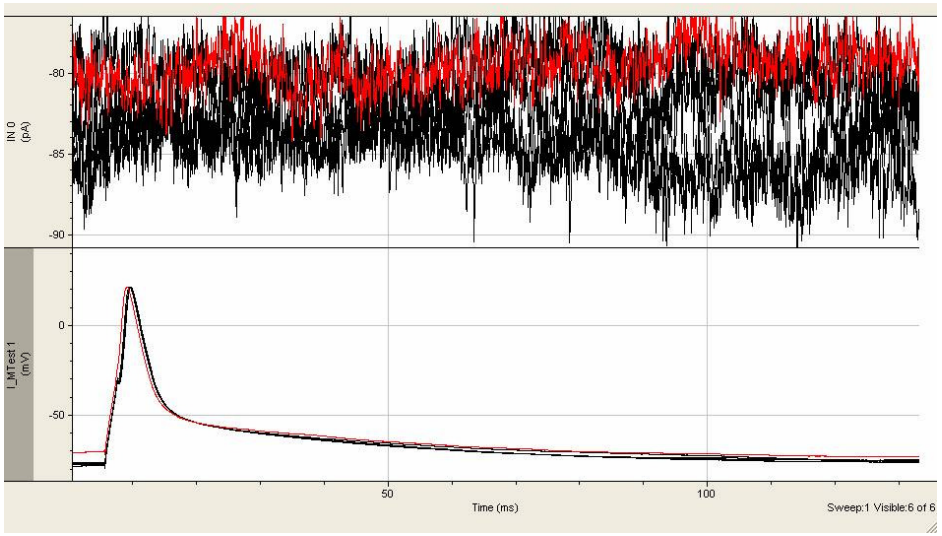



PHASE 20X
MAP2
MAP2
NF150
NF150


IN 0 (pA)
IN 1 (pA)
Time (ms)
Sweep:1 Visible:10 of 10


IN 0 (mV)
I_MTest 1 (mV)
Time (s)


IN 0 (mV)
I_MTest 1 (pA)
Time (ms)
Sweep:4 Visible:1 of 10

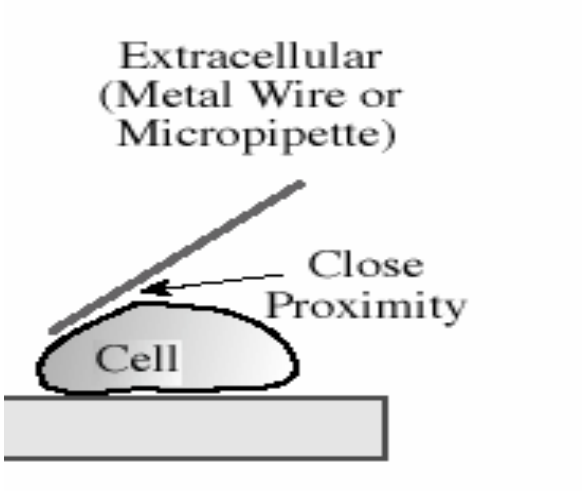

IN 0 (pA)
I_MTest 1 (mV)
Time (ms)
Sweep:1 Visible:6 of 6

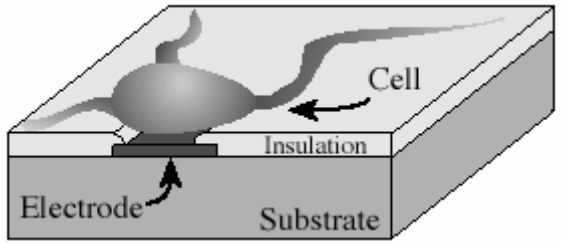
Extracellular Recording

Extracellular recording :

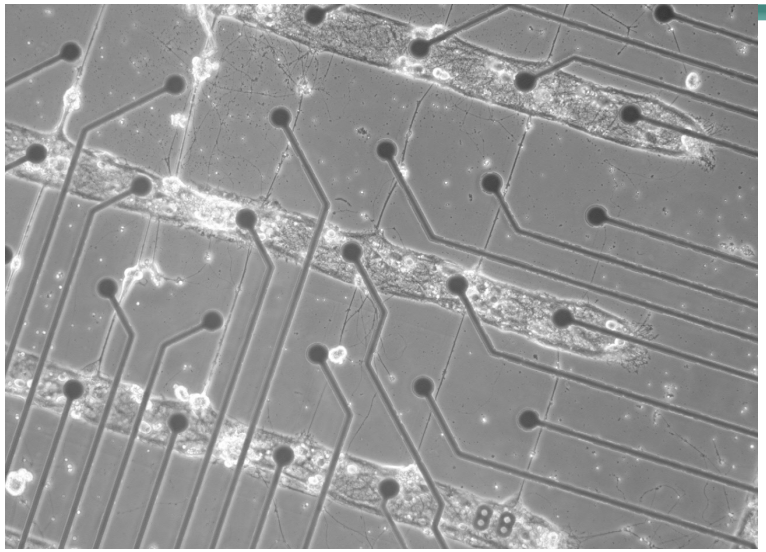
- two electrodes
- one close to the cell
- one reference in the bath

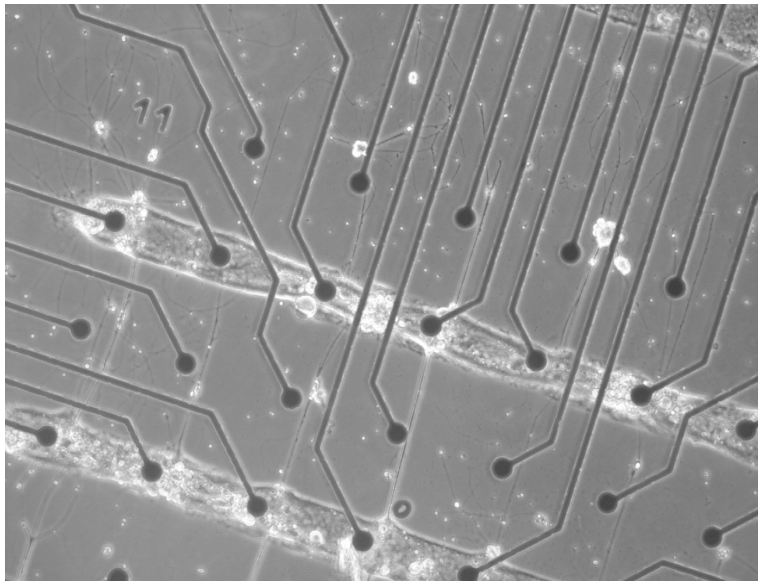
Result : Field potential

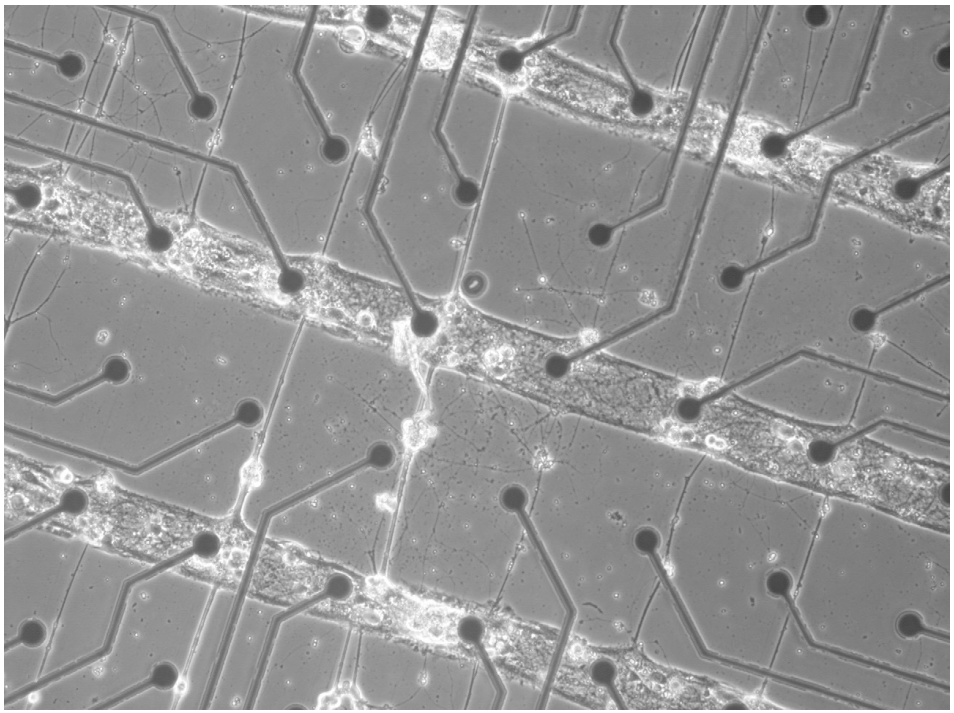


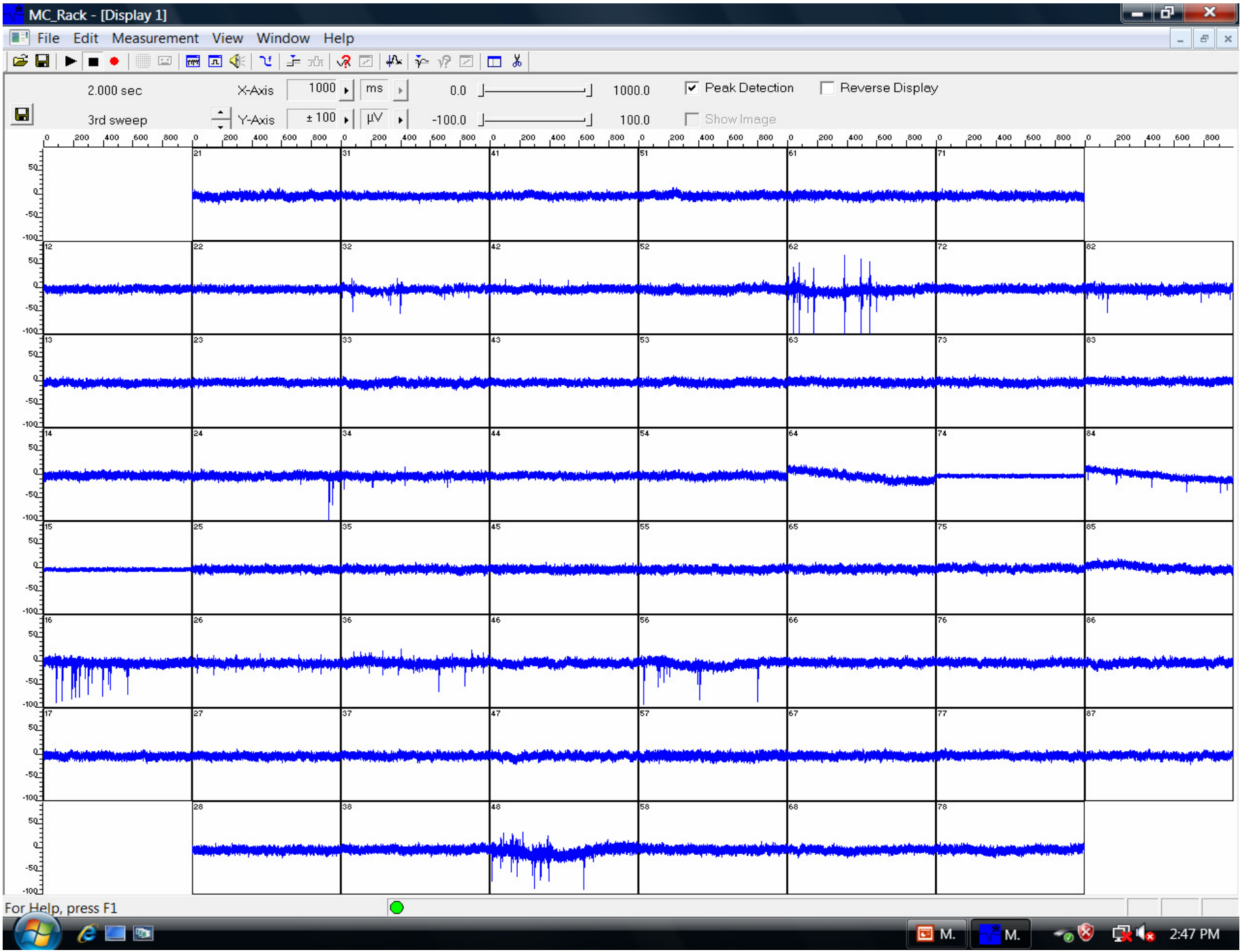


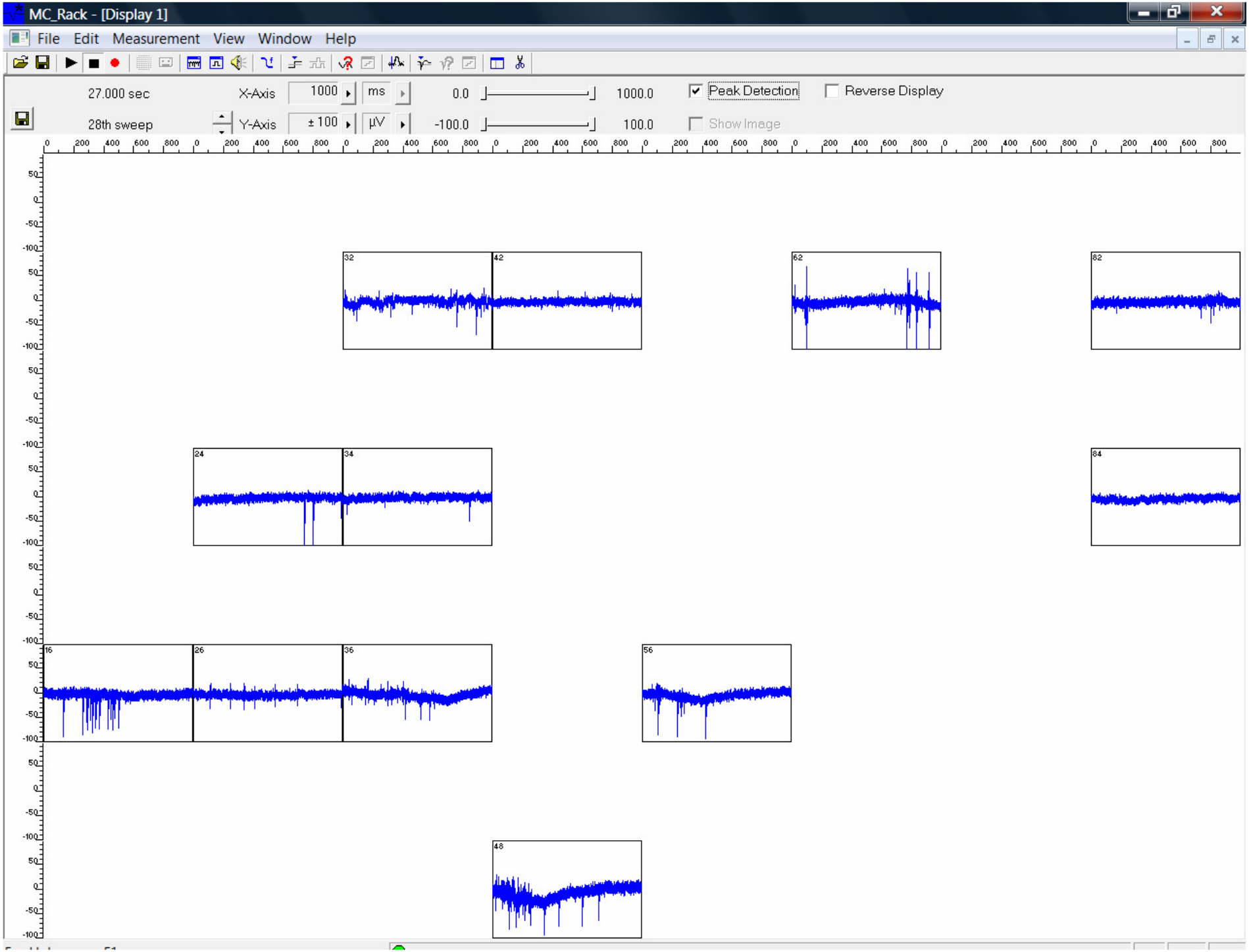
Hippocampal neurons, Day 18, NBActiV








MC_Rack - [Display 1]
File Edit Measurement View Window Help
2.000 sec
X-Axis
1000
ms
0.0
1000.0
Peak Detection
Reverse Display
3rd sweep
Y-Axis
± 100
µV
-100.0
100.0
Show Image
For Help, press F1
2:47 PM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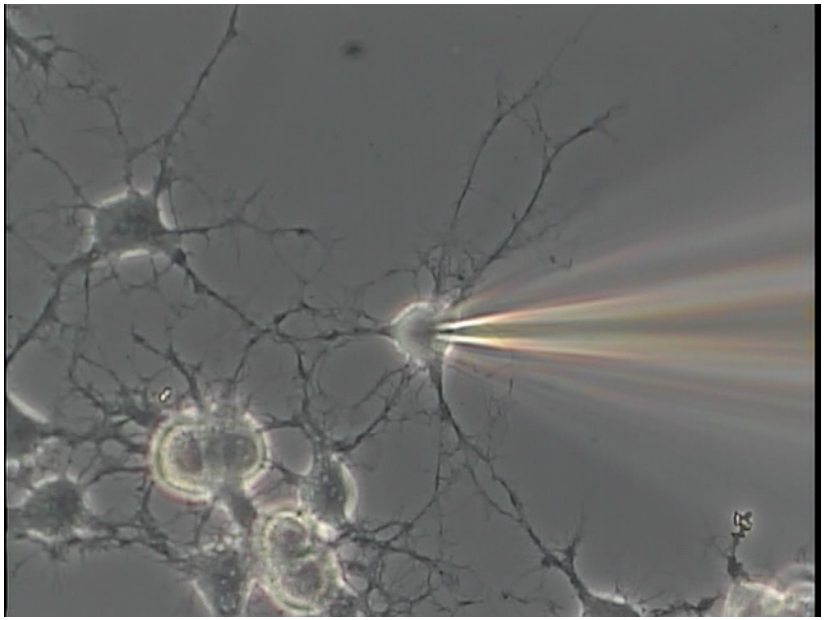
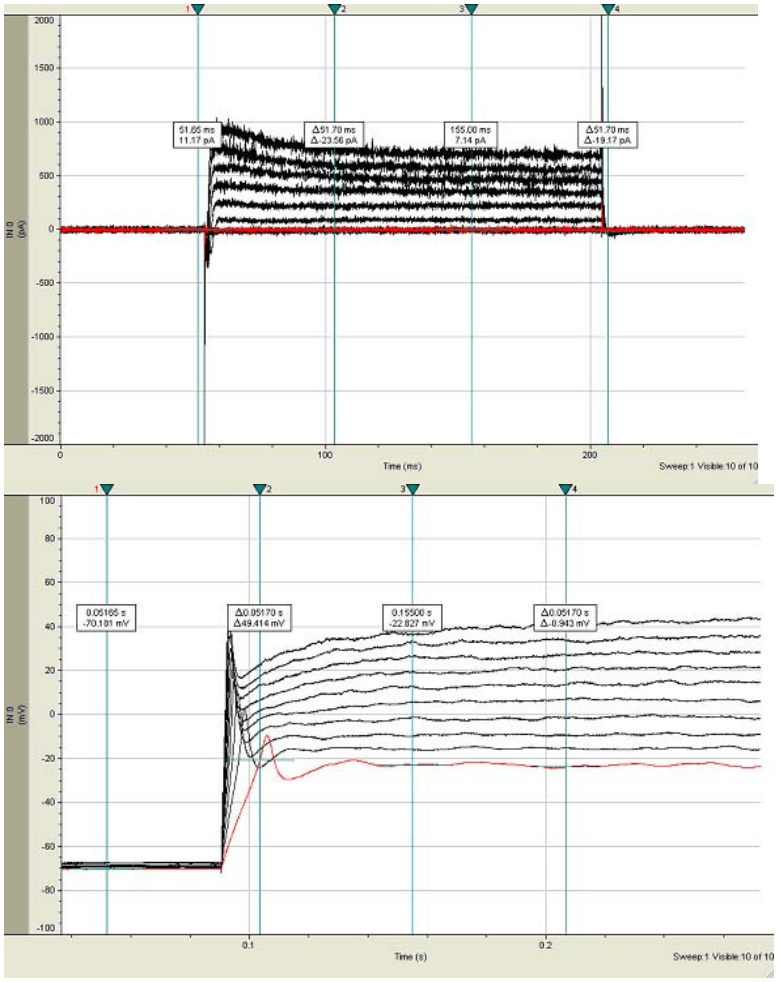
Y-Axis
± 100
µV
-100.0
100.0
Show Image
32
42
62
82
24
34
84
16
26
36
56
48

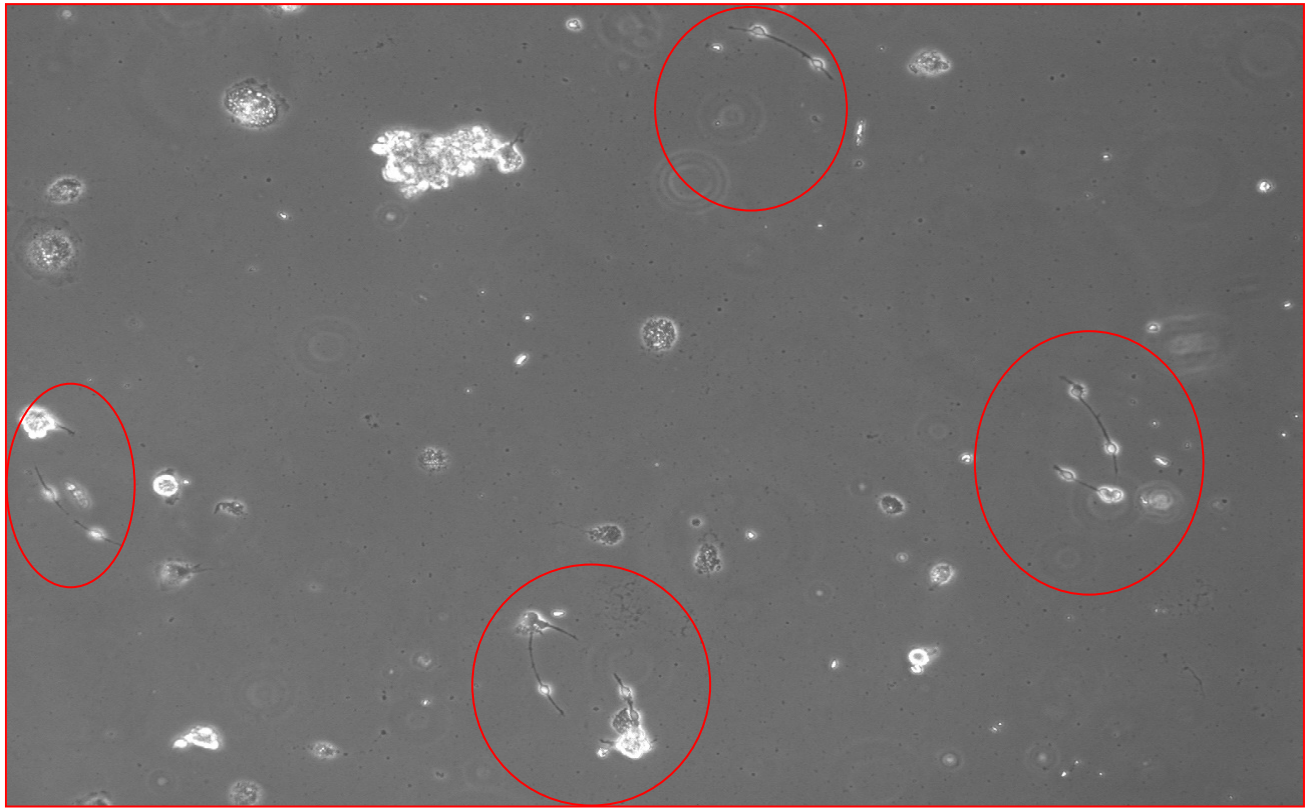
Adult hippocampal neurons two months post plating, positive electrical characteristics





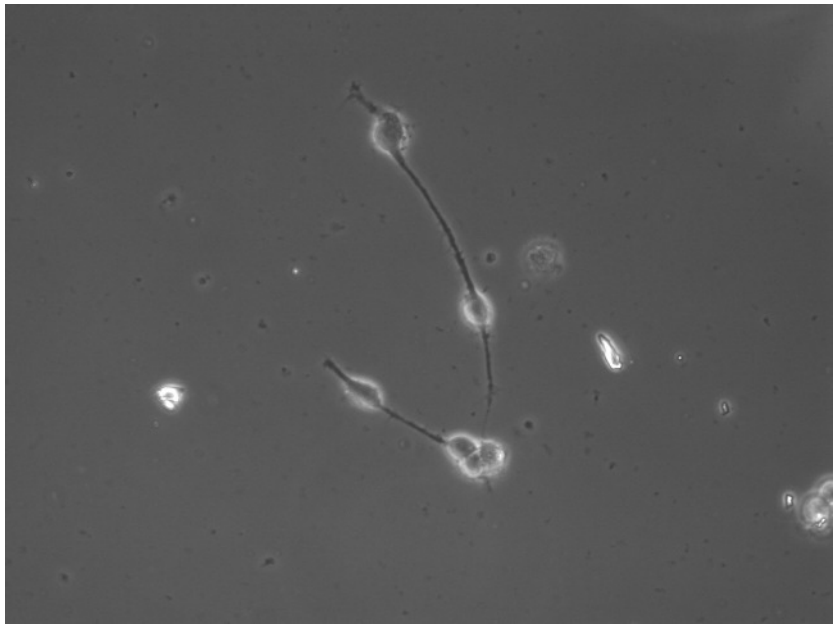
- **Inward and outward currents evident in current clamp mode**
- **Action potential seen firing in voltage clamp mode**

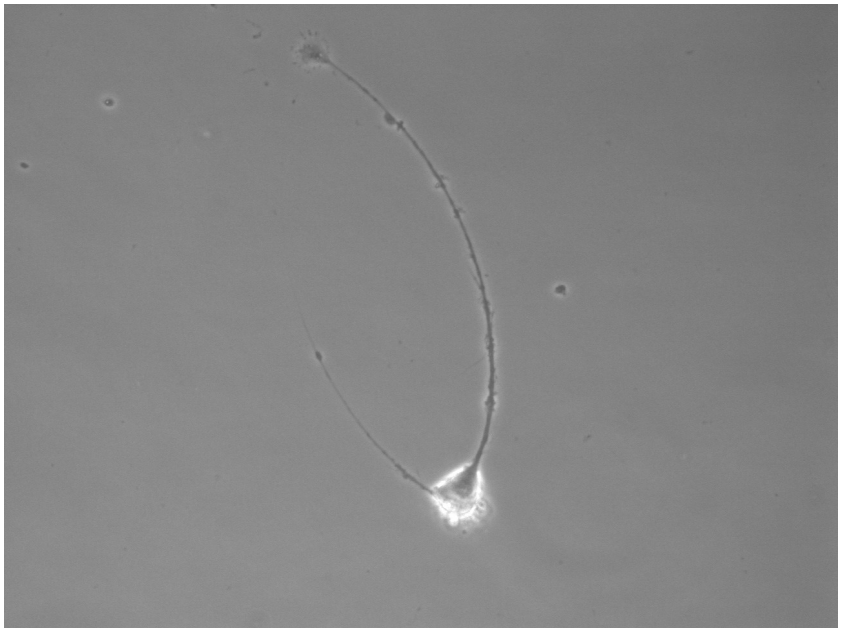
Adult patterned neurons on oval pattern (Fish Pattern)



- 10x view with multiple patterns forming (pattern formation not complete, neurites outgrowth ongoing)

Patterned neurons on oval pattern (Fish Pattern)



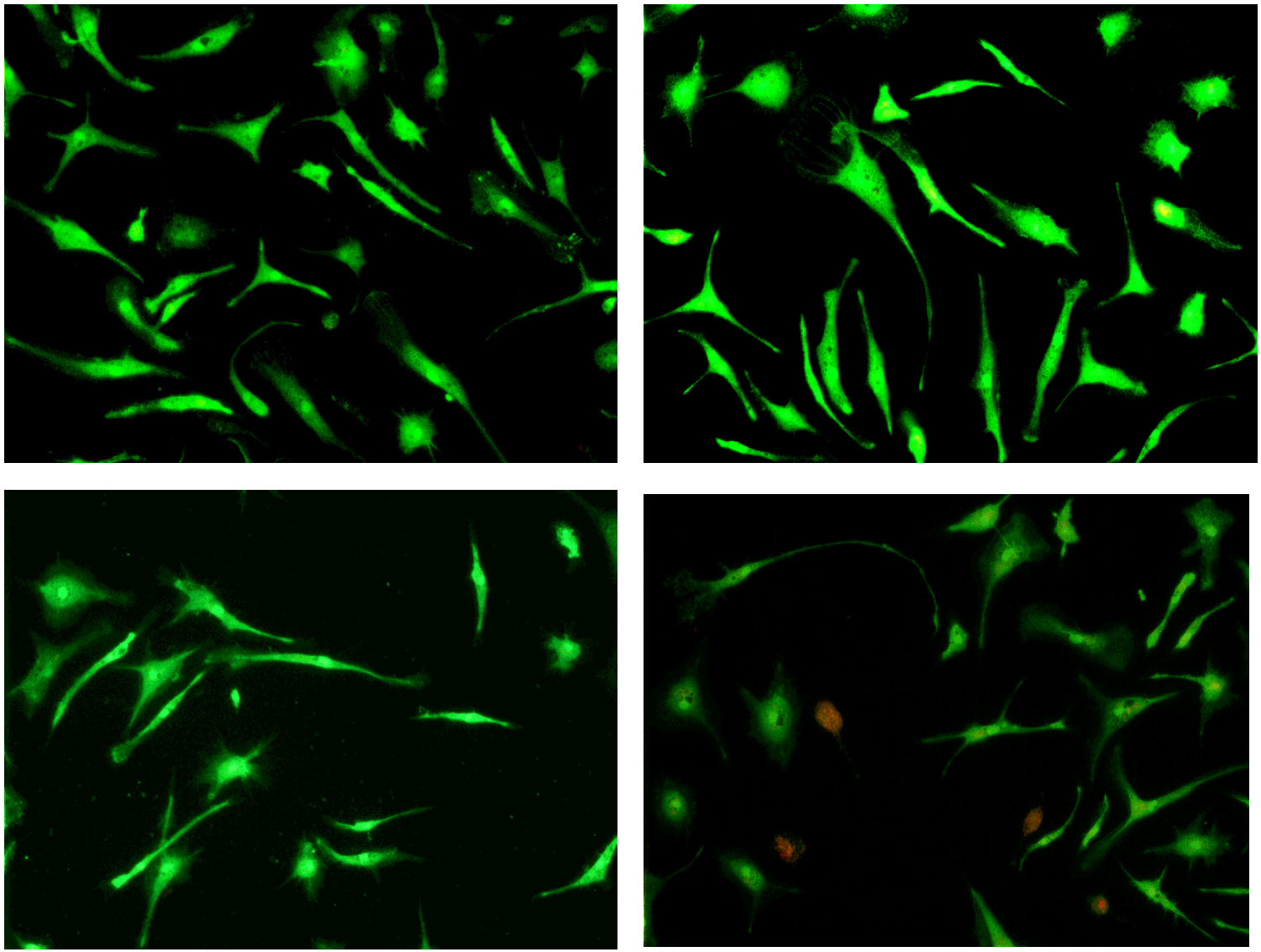


• Good cell body and neurite attachment to adhesive surface of patterns (Phase-contrast at 20x magnification)

CULTURING HIPPOCAMPAL NEURONS

- **Date :** 9/15/2007
- **Tissue type:** Hippocampus
- **Patient type:** AD
- **Pt Age:** 83
- **Sex:** F/ Caucassian

LIVE DEAD ASSAY OF THE CULTURE AFTER 6 DAYS IN CULTURE



LIVE CELLS: GREEN AND DEAD CELLS:RED

Assertions and Implications

- The second level of biological abstraction exists

- This allows information from a single source to be stored over multiple sites

- But most importantly, I believe it can be retrieved from multiple sites as a single agglomeration of information

- This resembles quantum information processing

- This may allow the equivalent of intuition to be realized

- These systems can be “built”

Remember in 1949 this was the extent of the electronics industry and look where that field is today. I would assert that this is about where the the field of bioelectronics is today and who knows where we can be in 10-20 years based on this example.