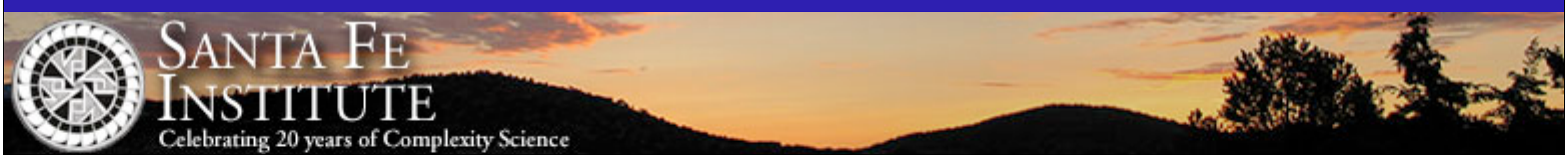
(What) Does The Brain Compute?

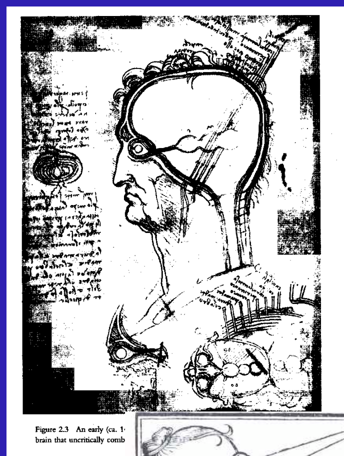
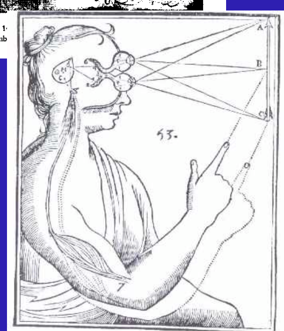
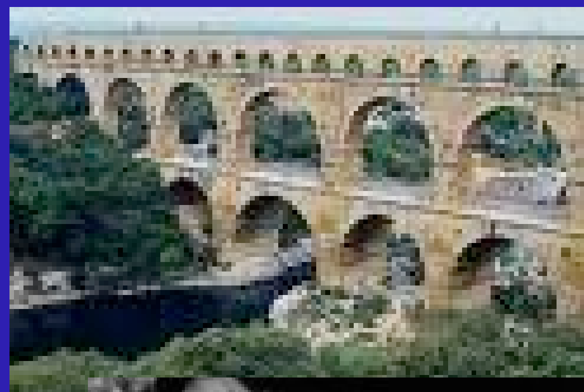
2nd ISCV Thematic Workshop
Biologically Inspired Computing

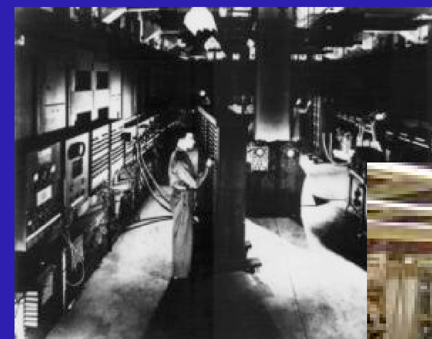
Valparaiso, Chile
December 3-7, 2007

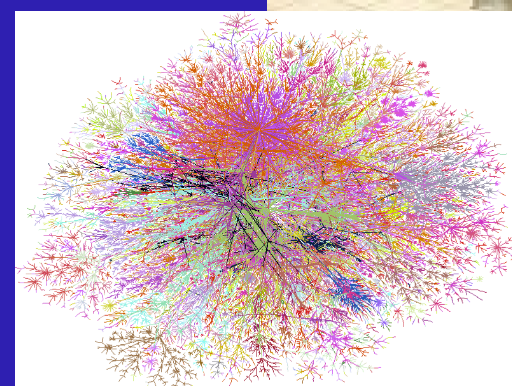
C. C. Wood
Santa Fe Institute



How Does the Brain "Work"?

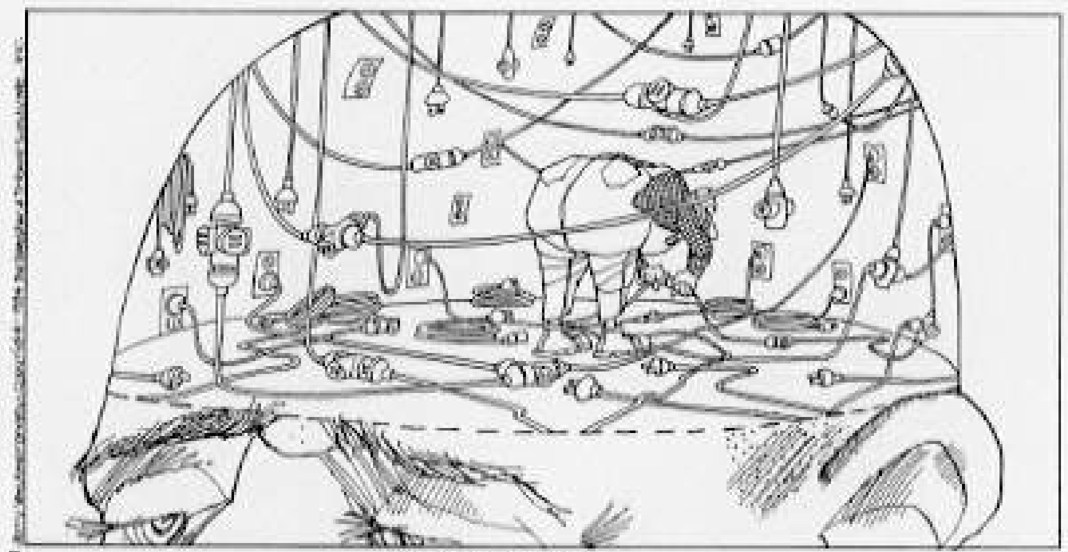






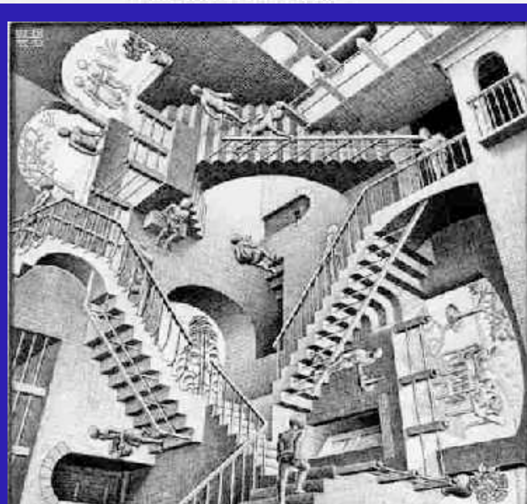


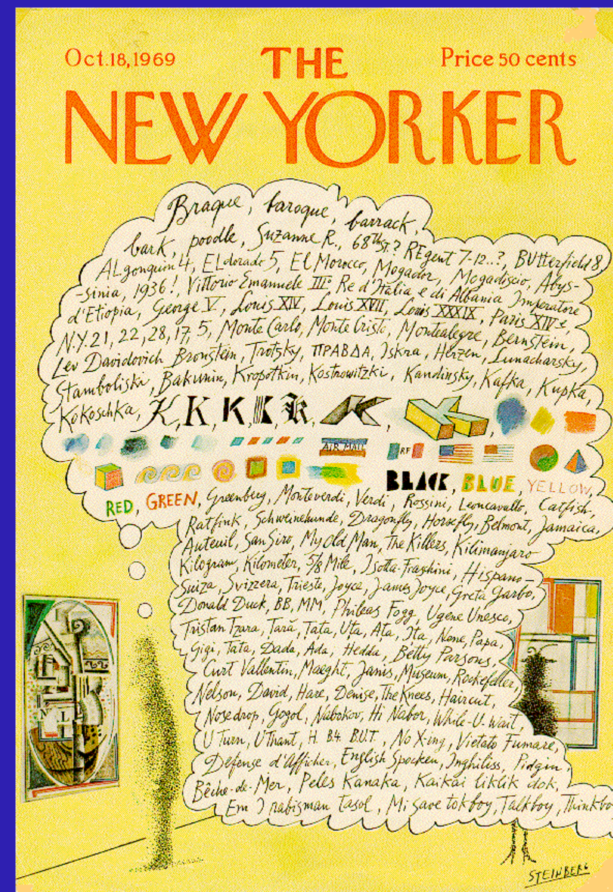
Throughout History, Theorizing about the Brain Has Emphasized the Most Sophisticated Technology Available at a Given Time: Aqueducts/Plumbing, Telephone Switchboards, Digital Computers, the Internet

“How the Brain Works”



How the brain works.





Where are the switches on this thing?

Asking the big questions in neuroscience.

23 Problems in Systems Neuroscience
edited by J. Leo van Hemmen & Terrence J. Sejnowski
Oxford University Press: 2006. 530 pp. £49, $79.95

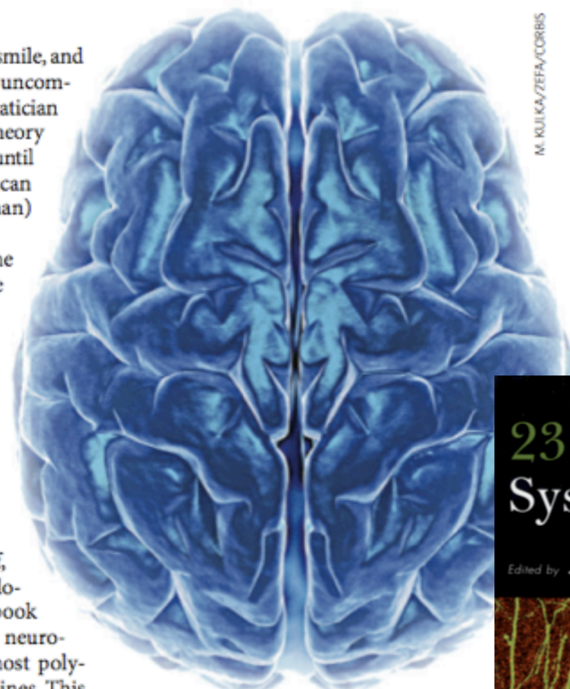
Kevan A. C. Martin

David Hilbert, in his opening address at the International Congress of Mathematicians in Paris in 1900, presented his colleagues with 23 problems whose investigation he thought would provide the major advances in mathematics in the twentieth century. Although about half of the problems remain unsolved, history shows that mathematicians rose splendidly to the challenge.

Neuroscience has a rather briefer history than mathematics, but Leo van Hemmen and Terry Sejnowski felt that it was nonetheless mature enough for them to organize a meeting on 'Problems in Neuroscience' a century after Hilbert's address. This printed version of their meeting, *23 Problems in Systems Neuroscience*, has taken six years to arrive, but it is not too late and certainly not too little. In the place of one Hilbert are 40 problem-posers who have collectively contributed the 23 chapters, grouped into sections that sum up 5 current concerns: How have brains evolved? How is cerebral cortex organized? How do neurons interact? What can brains compute? How are

The writing frequently made me smile, and often it comes close to realizing the uncommon view of an old French mathematician retold by Hilbert: "A mathematical theory should not be considered complete until you have made it so clear that you can explain it to the first man (or woman) whom you meet on the street."

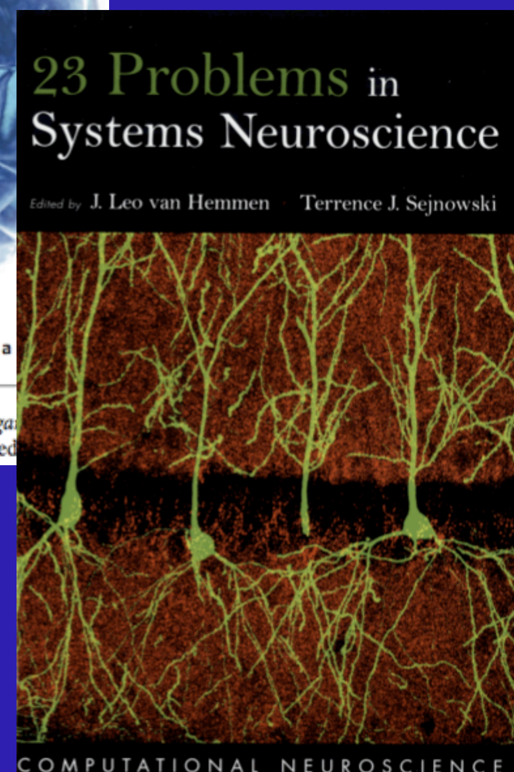
Like Hilbert, the authors assume that their problems can and will be solved. However, unlike mathematical problems, those of systems neuroscience will not be solved by pure reason, but will require the integration of experiment and theory, and perhaps even a new science that incorporates the subjective. In this context it would be interesting to know how many of the authors originally trained as neuroscientists or even biologists. If, as I suspect, card-carrying neurobiologists are in the minority, then this book exposes the deep, dark secret that neuroscience has become one of the most polymathic of modern scientific disciplines. This is as it should be, because neuroscience faces the most intractable questions in modern science and we need all hands on deck if we are to find a safe passage through the problems raised here.



M. KULKA/ZEFA/CORBIS

Neuroscience would be much easier if we had a detailed circuit diagram of the brain.

of every model animal, *Caenorhabditis elega*
excepted, and this remains a major imped



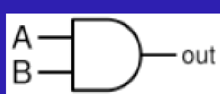
In What Sense Does the Brain "Compute"?

Key Distinction Between the Abstract "Computational Level" and the Physical Substrate

Logic Gates in Digital (Von Neumann / Turing) Computers

AND

INPUT		OUTPUT
A	B	A AND B
0	0	0
1	0	0
0	1	0
1	1	1

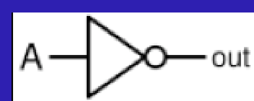


OR

INPUT		OUTPUT
A	B	A OR B
0	0	0
1	0	1
0	1	1
1	1	1

NOT

INPUT	OUTPUT
A	NOT A
0	1
1	0



NAND

INPUT		OUTPUT
A	B	A NAND B
0	0	1
1	0	1
0	1	1
1	1	0

NOR

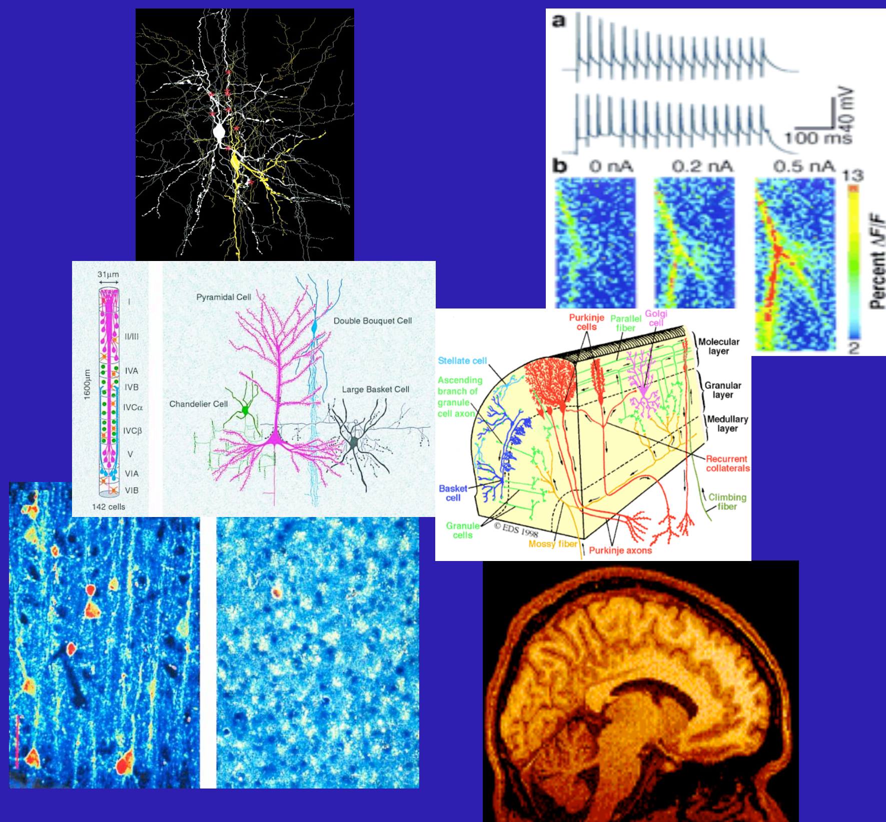
INPUT		OUTPUT
A	B	A NOR B
0	0	1
1	0	0
0	1	0
1	1	0

Together, these logical operations implement

Two Key *"Computational Primitives"* for Digital Computation:

Boolean Logic and Binary Arithmetic

Are There Analogous "Computational Primitives" for the Brain?



?

Digression I: The Software-Hardware Distinction is a "Red Herring" for Biological Computation

American Heritage Dictionary - *Cite This Source* - *Share This*

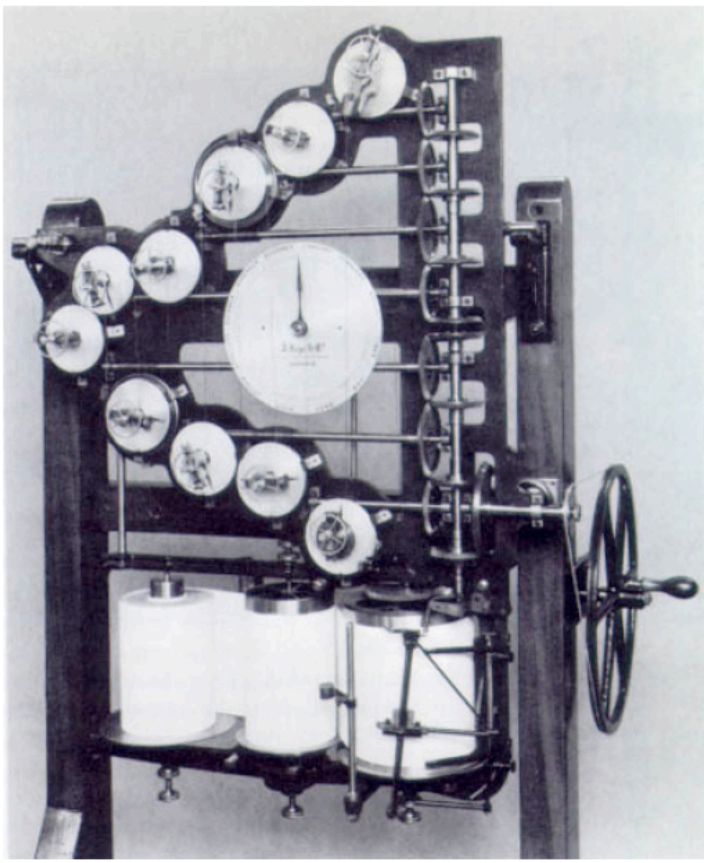
red herring

n.

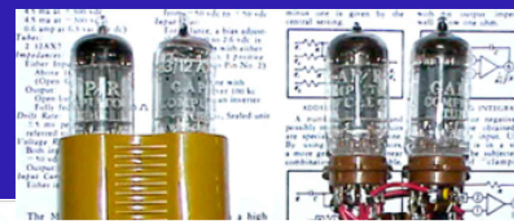
1. A smoked herring having a reddish color.
2. Something that draws attention away from the central issue.

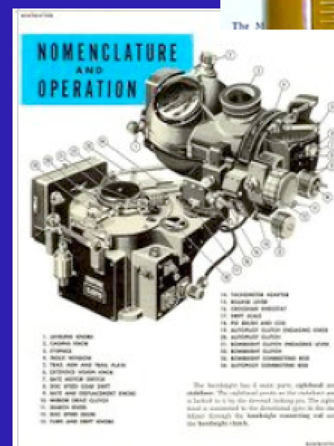
Digression 2: Analog Computation:

A Rich but Under-Explored Alternative to Digital Computation (for very good reasons...) and Likely a Fertile Metaphor for Neural "Computation"



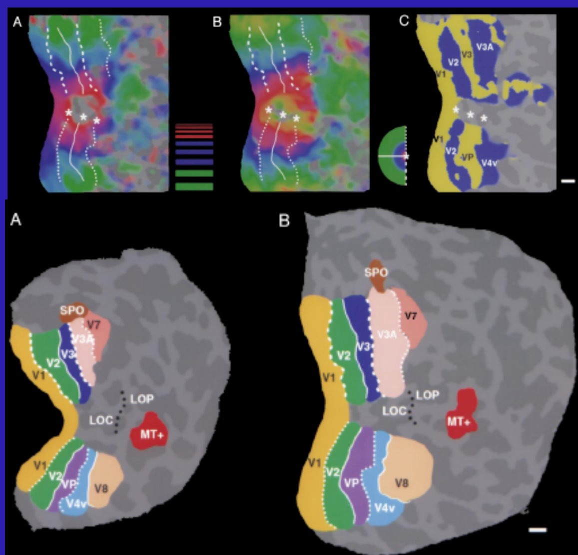
Kelvin's Tide Predictor (1876-1878)

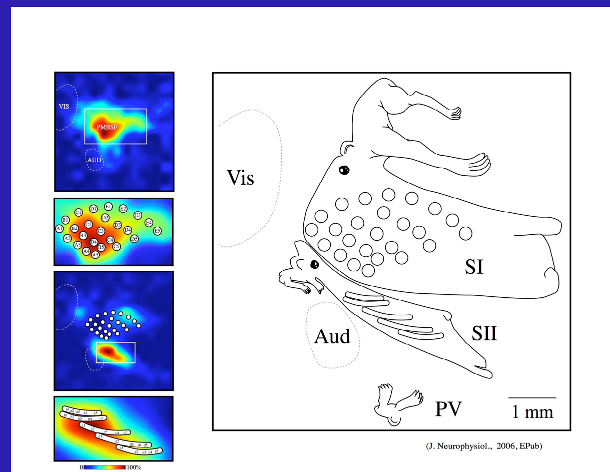


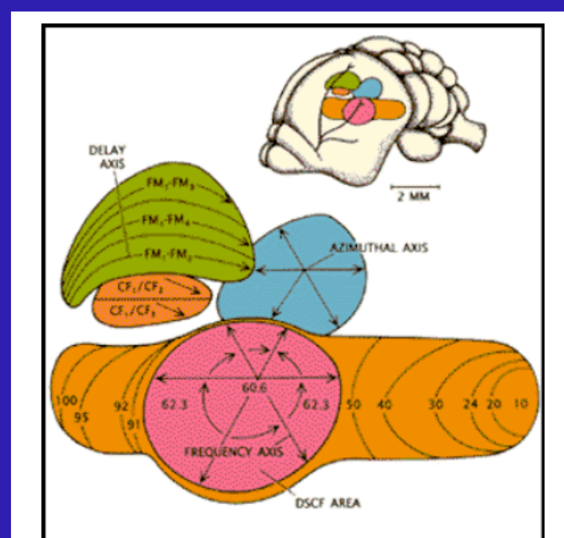


A page from the *Bombardier's Information File* (BIF) that describes the components and controls of the Norden bombsight. The **Norden bombsight** was a highly sophisticated optical/mechanical analog computer used by the United States Army Air Force during World War II, the Korean War, and the Vietnam War to aid the pilot of a bomber aircraft in dropping bombs accurately.

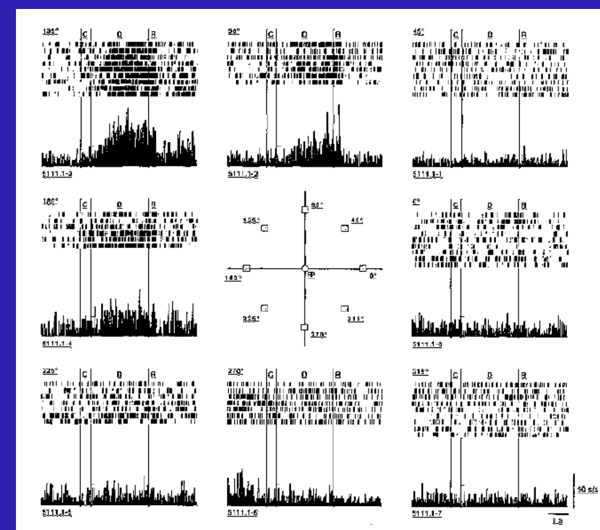
Candidate “Computational Primitives” for the Brain:
1. Topographic Representations and Transformations?





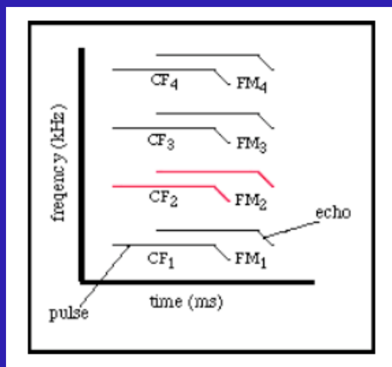


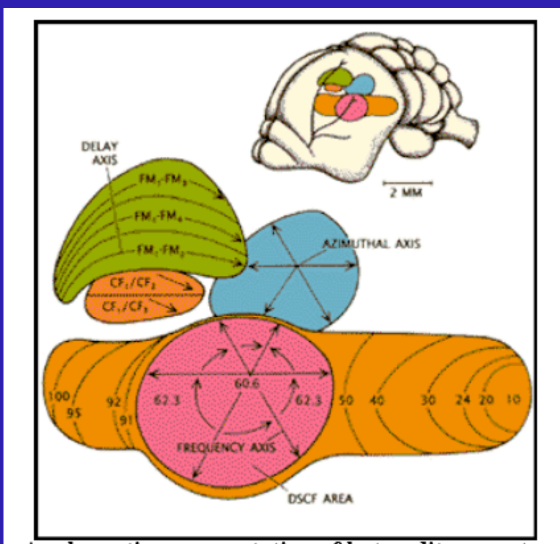
A schematic representation of bat auditory cortex



Auditory Cortex Organization in Bat and Monkey

Single Cell Recordings in the Bat ("What it is like to be a…")

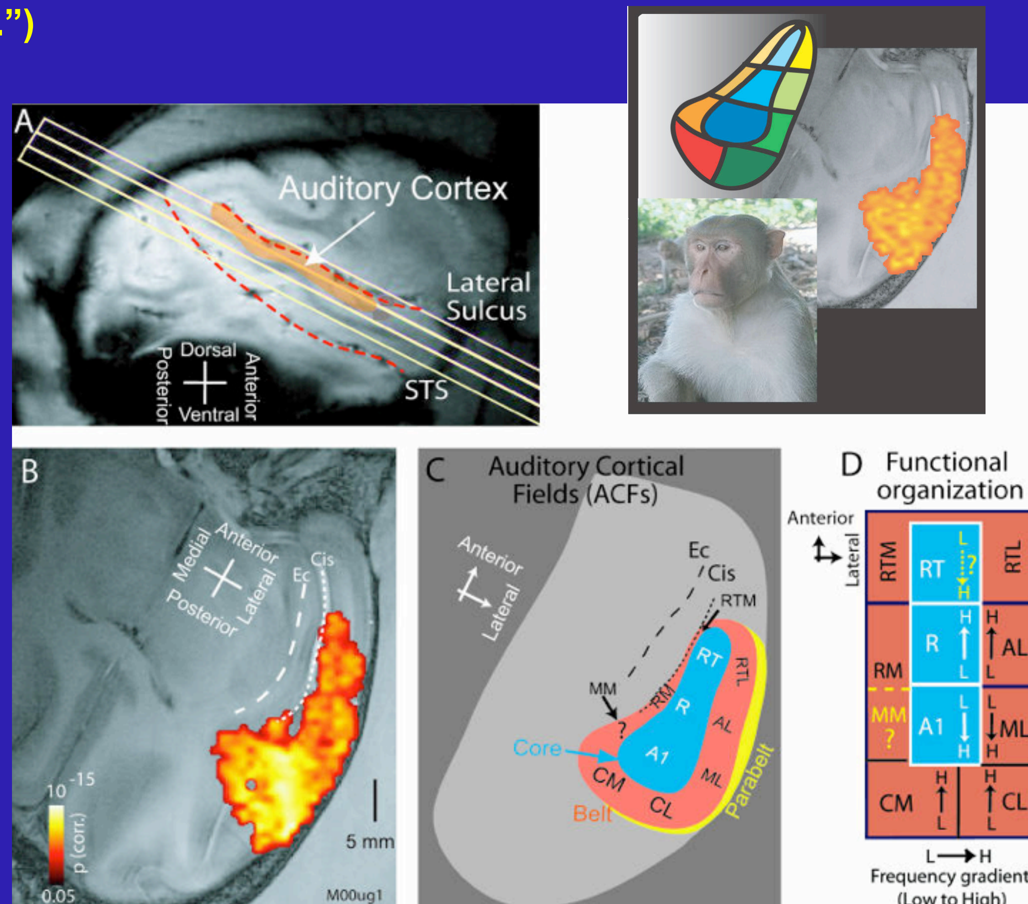




A schematic representation of bat auditory cortex

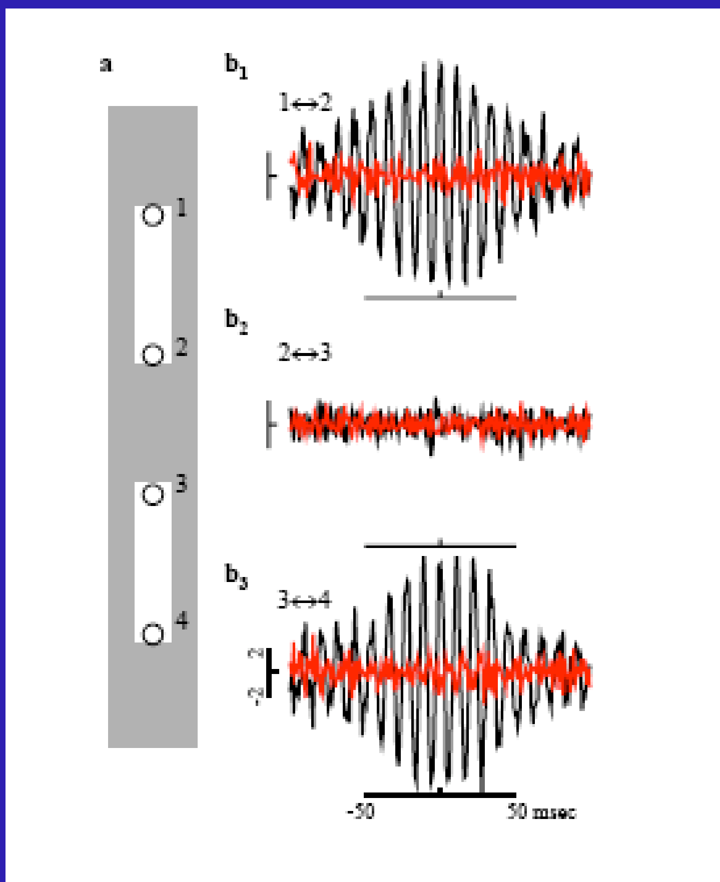
Suga et al.

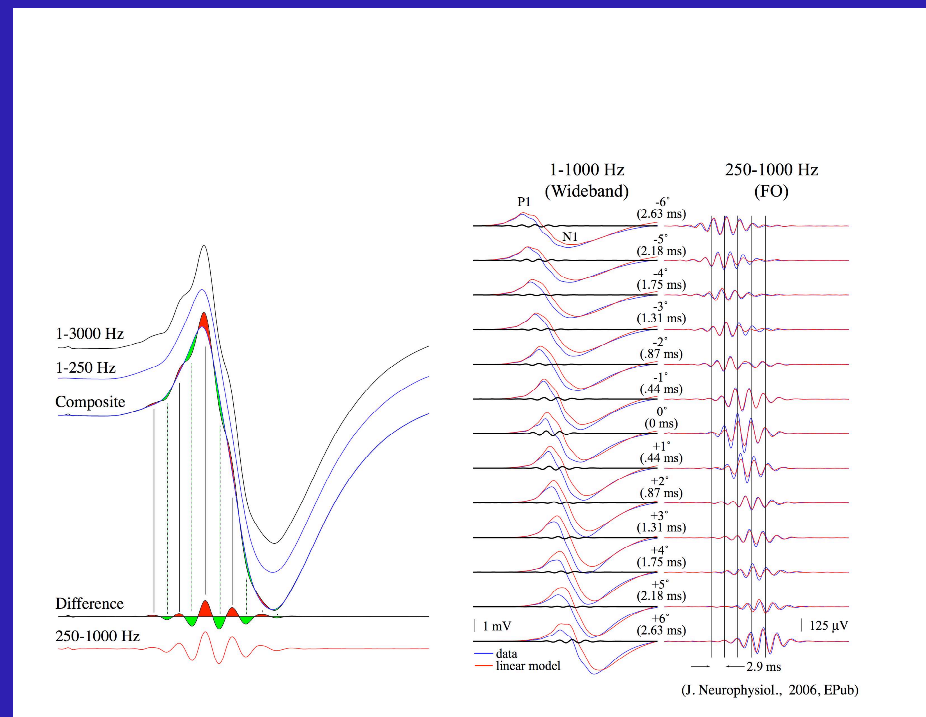
fMRI Data in Monkey



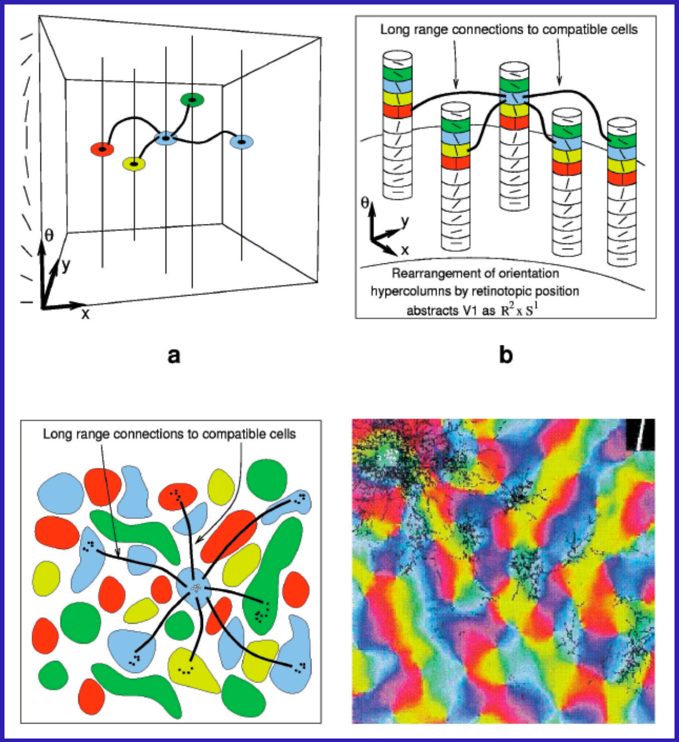
Logothetis et al.

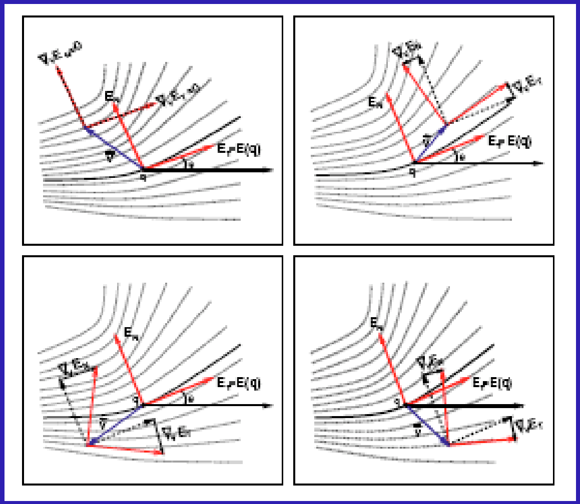
Candidate “Computational Primitives” for the Brain:
2. Coherent Oscillations / Synchronization?

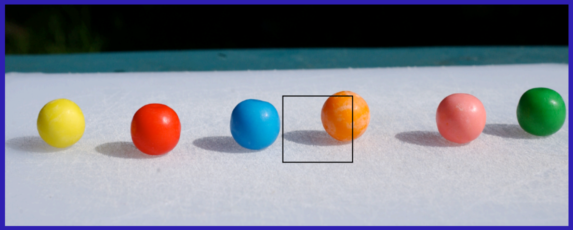


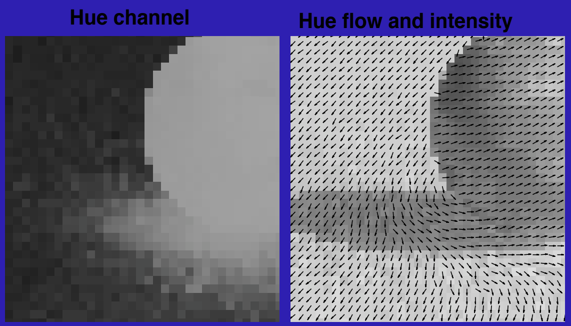


Candidate "Computational Primitives" for the Brain: 3. Differential Geometry (Zucker et al.)

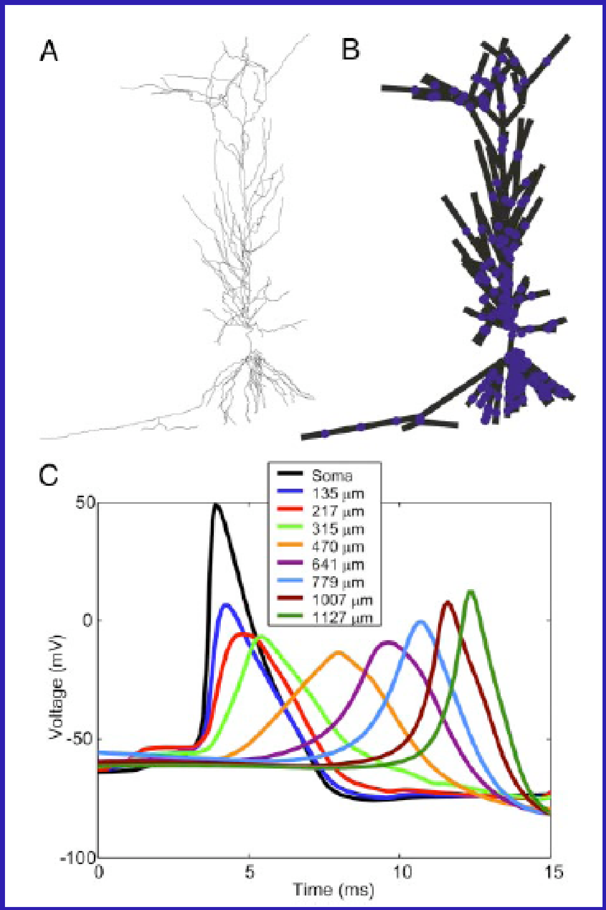






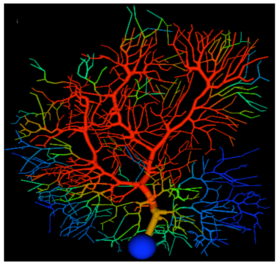


Candidate "Computational Primitives" for the Brain: 4. Hebbian Synapses and Spike-Timing Dependent Plasticity?



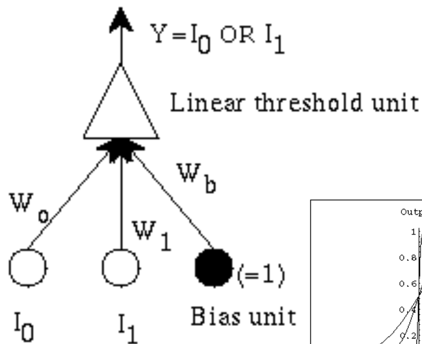
Others?

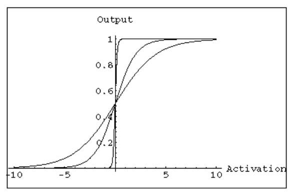
Insert Your Favorite Here!

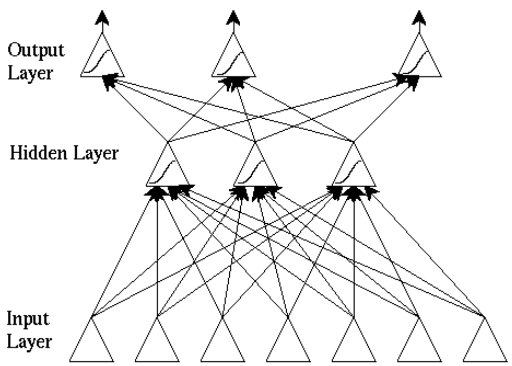


Modeling Neurons, Neural Circuits, and Neural Systems: Two Approaches with Different Levels of "Realism"

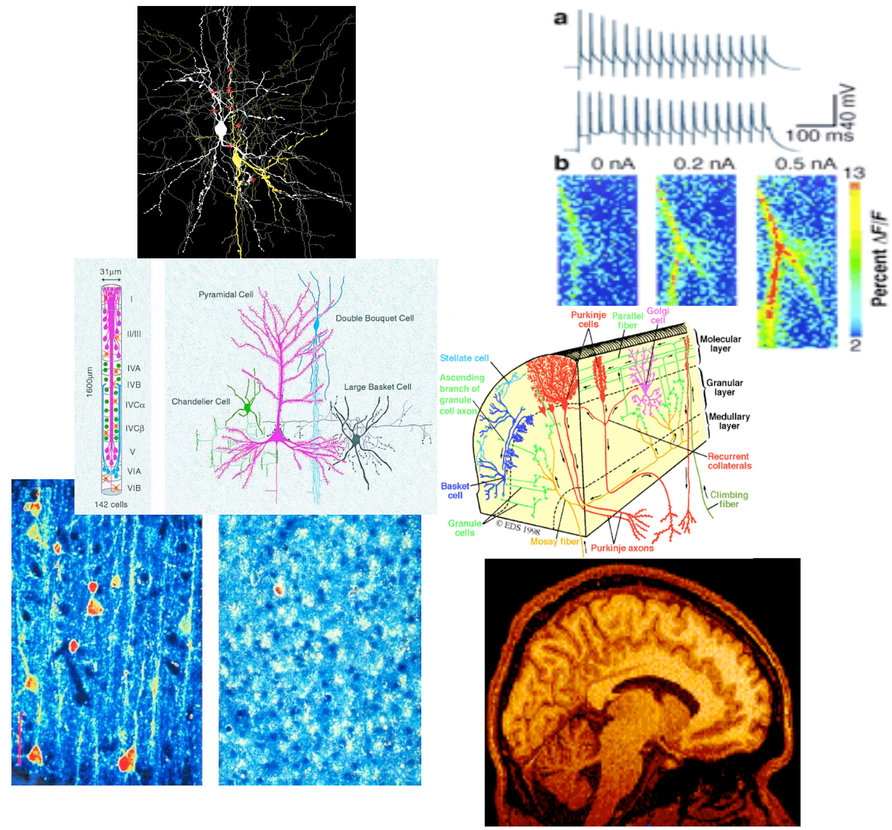
"Artificial" Neural Networks

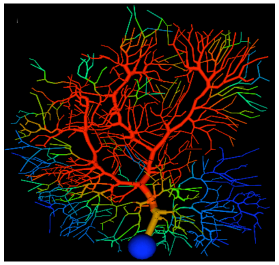






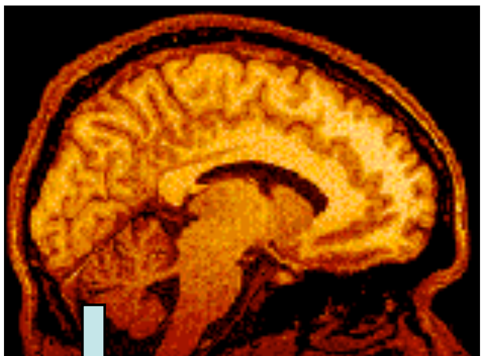
"Realistic" Neurons, Circuits, and Systems

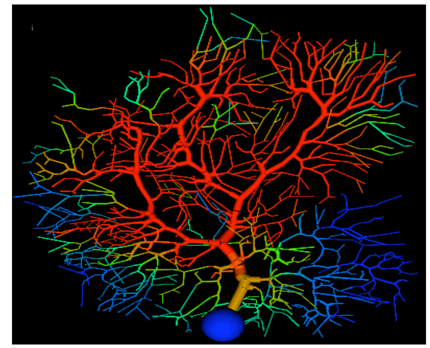




Modeling Cerebellar Purkinje Cells

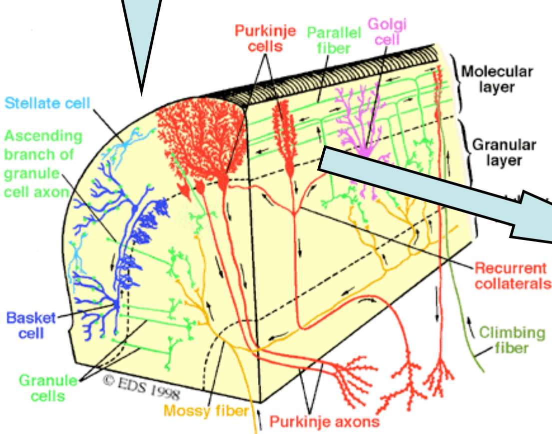
High-Resolution Compartmental Model of a Cerebellar Purkinje Cell



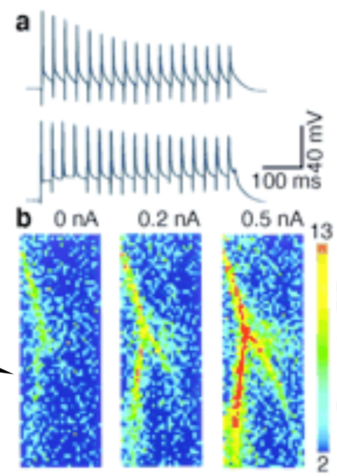


Cerebellum in MRI Image

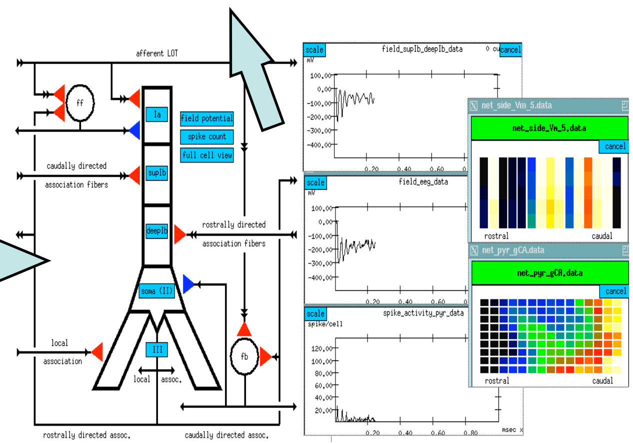
Bower and De Schutter, UTHSC, Antwerp



Schematic of Cerebellar Cellular Architecture

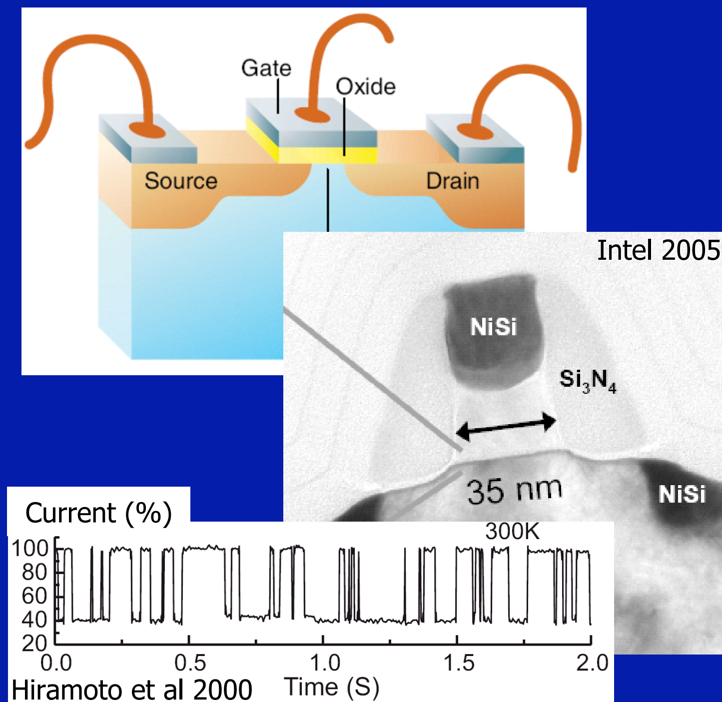


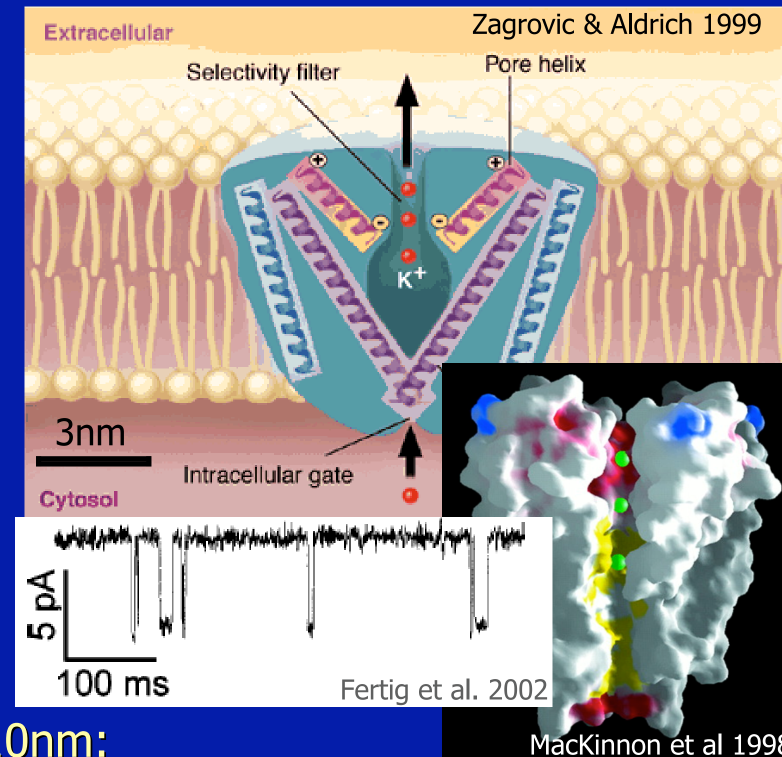
Example of Single Cell Recordings



GENESIS Neuronal Modeling System
Wilson, Bower, De Schutter et al.

2.1 Transistor versus ion-channel





In 10yrs, when transistors shrink to 10nm:

- ❖ They will become stochastic—just like an ion-channel
  - ➢ One trapped electron reduces current flow significantly
- ❖ The brain can teach us how to compute this way
  - ➢ Present analog and digital paradigms breakdown

Conclusions: What Do We Mean by "Computation" in "Neural Computation"?

Two Fundamental Distinctions:

1. **Abstract "Computational Primitives" versus Physical Substrate**

2. **Principles (of "System Design and Organization") versus Patterns (in the Data)**

(What) Does The Brain Compute?

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Santa Fe Institute