What Kind of Computer is the Brain?

International Council on Systems Engineering
INCOSE Enchantment Chapter
February 12, 2014
Albuquerque, New Mexico

C. C. Wood
Vice President, Administration
Santa Fe Institute

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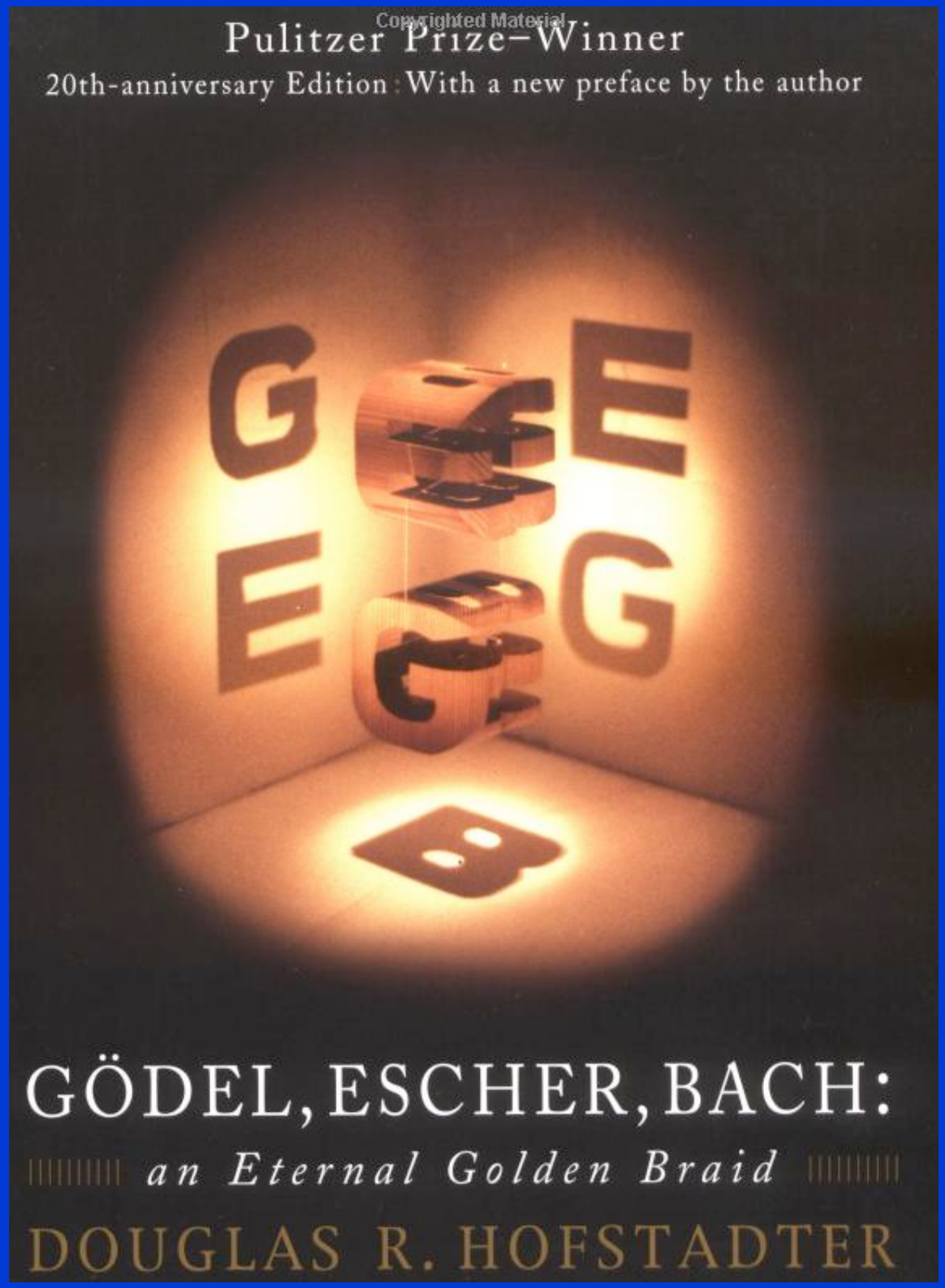

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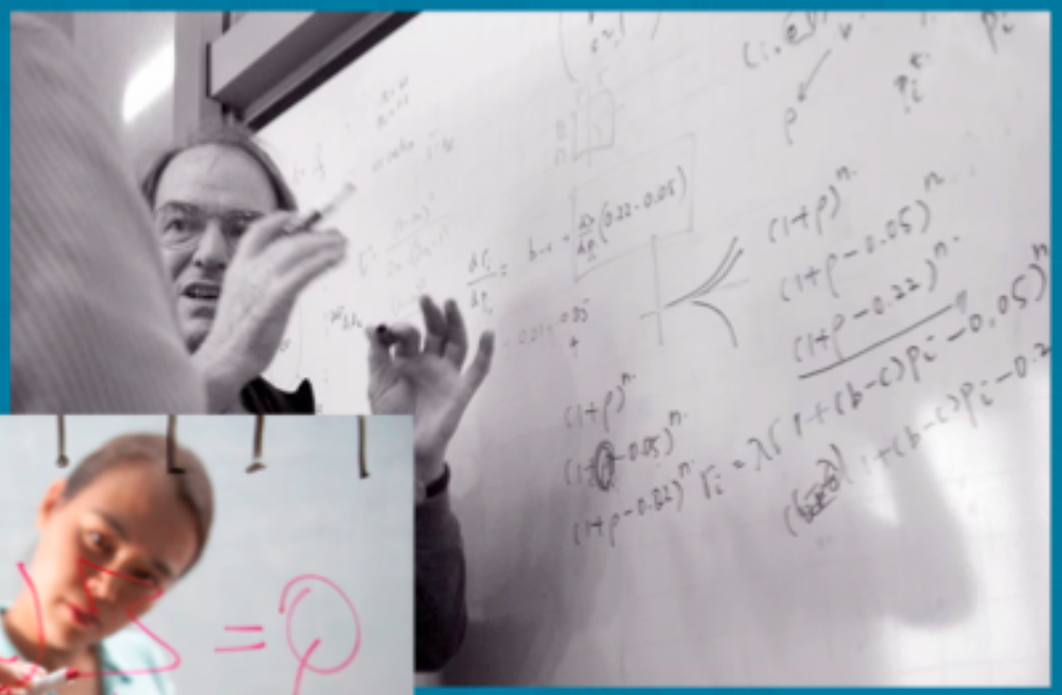
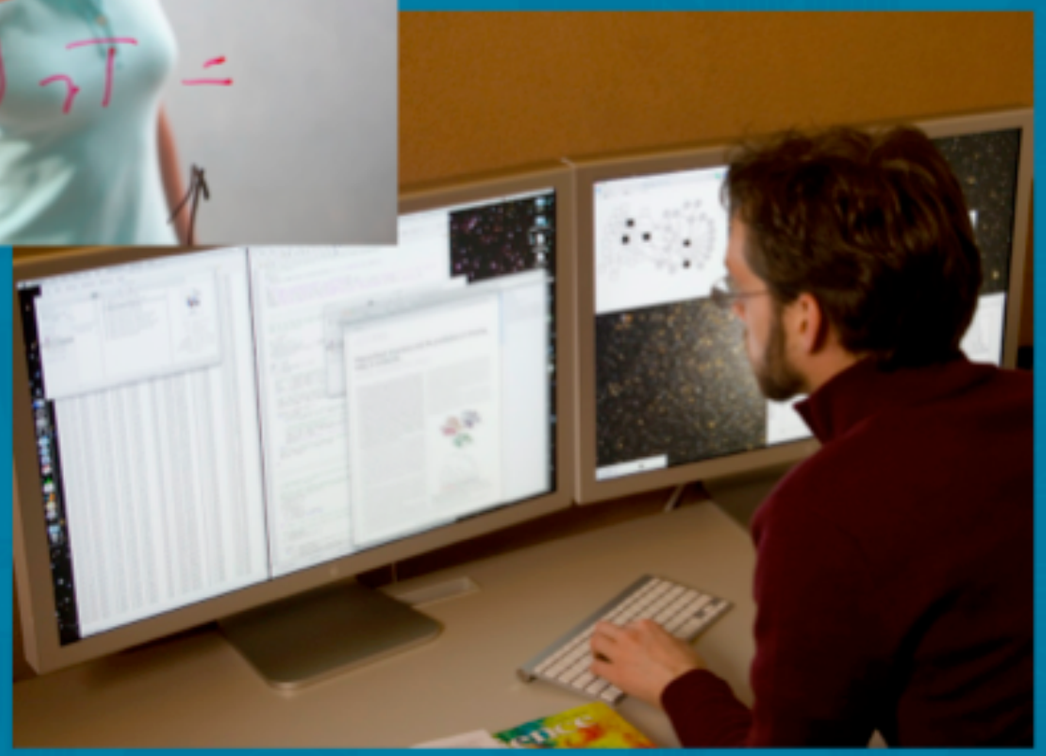
complexity research expanding the boundaries of science

Trans-disciplinary science addressing the world's most challenging problems





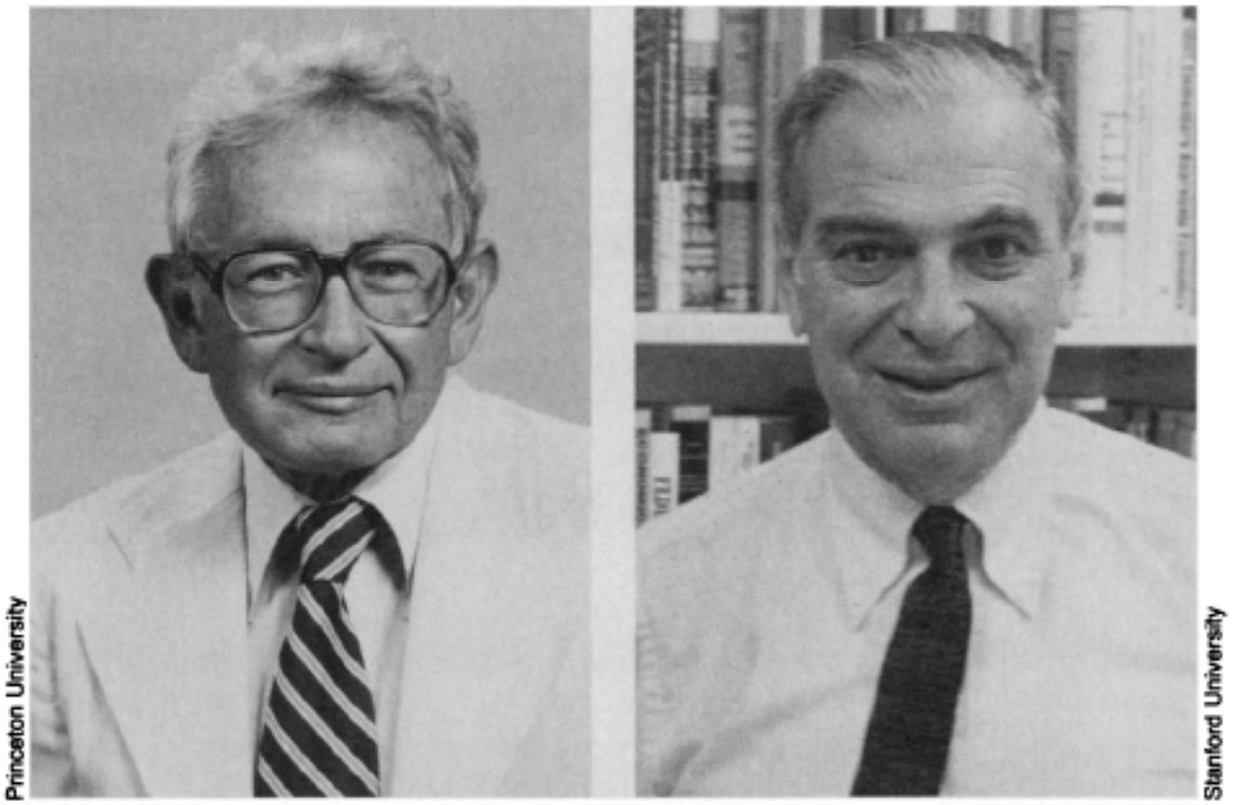
Research News

Strange Bedfellows

It is hard to think of a more unlikely collaboration than one between physicists and economists, but this is exactly what is going on at a former convent in Santa Fe, New Mexico

THEY MAKE AN ODD COUPLE, these two Nobel laureates. Philip Anderson is a condensed matter physicist who specializes in superconductivity; Kenneth Arrow is a theoretical economist who studies such things as how markets react to uncertainty. At first sight, you wouldn't expect them to have much in common, but you would be wrong.

Over the past 2 years, Anderson and Arrow have worked together in a venture that is one of the oddest couplings in the history of science—a marriage, or at least a serious affair, between economics and the physical sciences. If this unlikely liaison bears fruit, the result could be a hybrid theory that imparts to economics some of the tools and techniques developed for such fields as physics and biology.



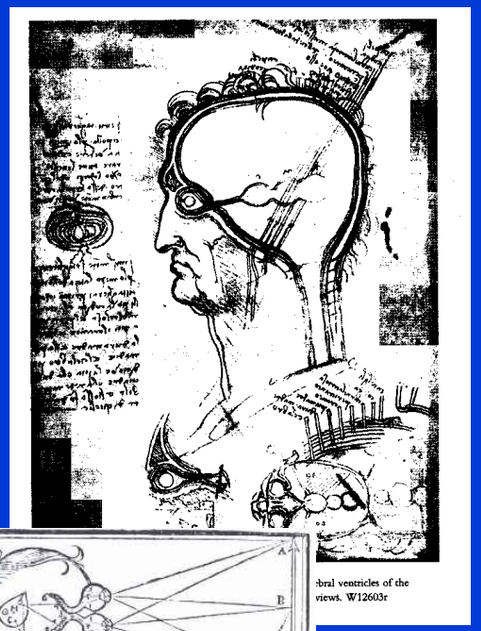
Physicist and economist. *Anderson (left) and Arrow kicked off an unusual collaboration by inviting ten physical scientists and ten economists to meet in Santa Fe.*

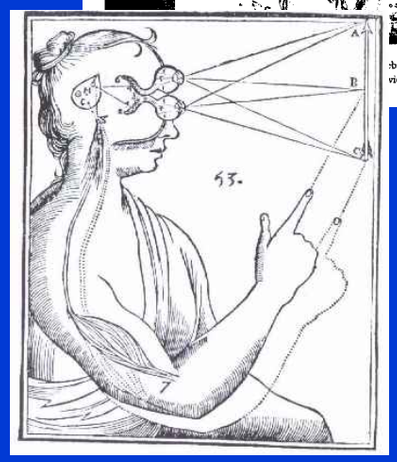
Although the project may seem somewhat quixotic, its roots are deep in the practical soil of the business world. In 1986, John Reed, chairman of Citicorp, found himself dissatisfied with state-of-the-art economic best science and economics schools in the country—places such as Princeton, Caltech, Stanford, and Chicago.

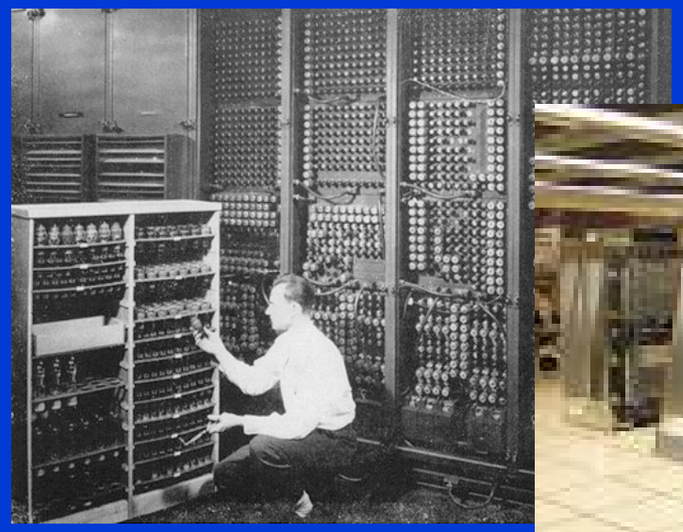
As might be expected, the economists and scientists have found that things get rather interesting when two such different cultures collide.

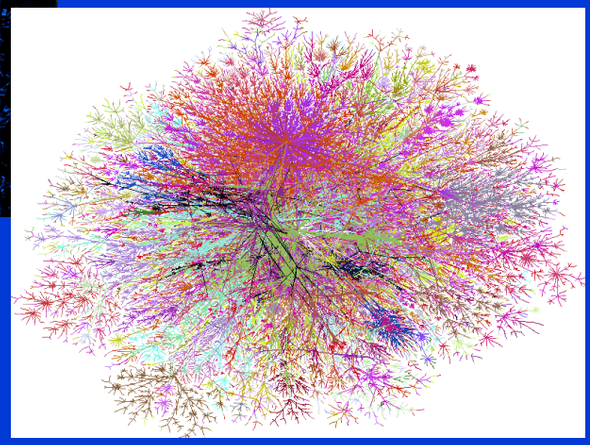
Richard Palmer, a physicist at Duke University, recalls that first meeting in September 1987. "I used to think physicists were the most arrogant people in the world," he says. "The economists were, if anything, more arrogant." Both groups came into the meeting with skepticism and preconceived ideas, he recalls. The economists felt the physical scientists could not possibly help with their problems, and the physical scientists thought economics was a mess and there was not much you could do with it.

So: How Does the Brain "Work"?



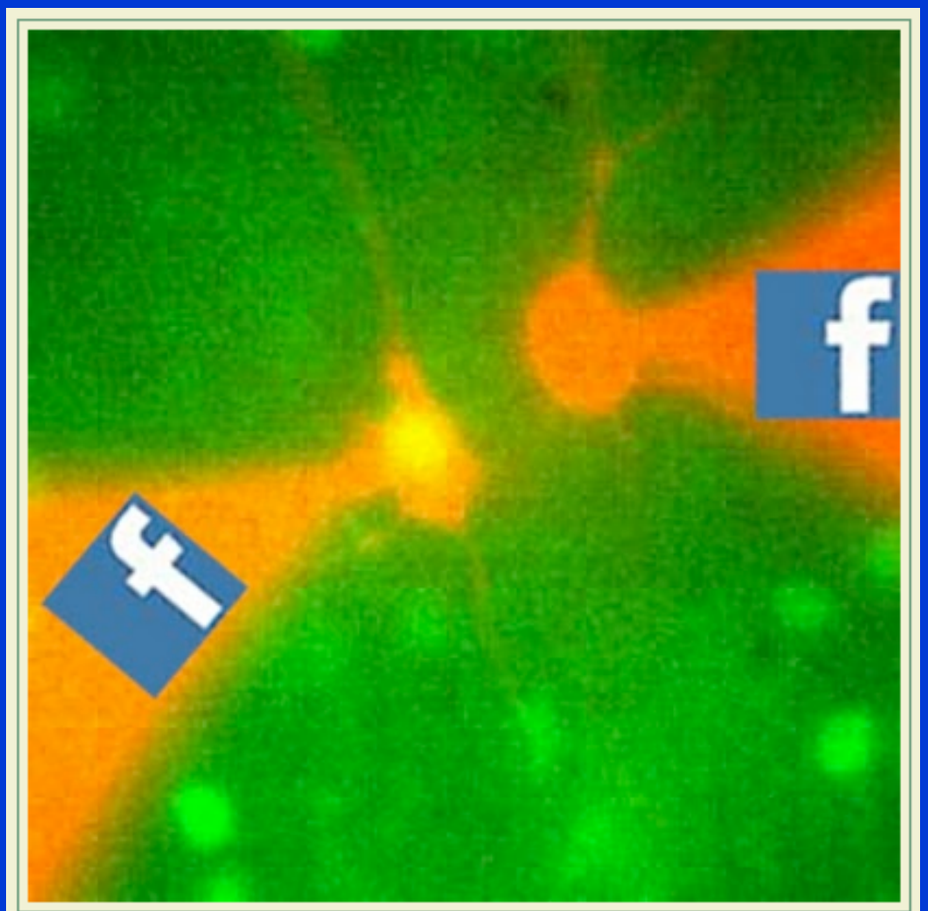






Throughout History, Theorizing about the Brain Has Used as Metaphors the Most Sophisticated Technology Available at the Time: Aqueducts/Plumbing, Telephone Switchboards, Digital Computers, Supercomputers, the Internet, the "Cloud"...

Researchers Identify 'Facebook Neurons': Population of Highly Active Neurons Could Provide Insight Into the Neocortex



Paired cell recording from the cerebral cortex of the fosGFP transgenic mouse. (Credit: Image courtesy of Carnegie Mellon University)

The New York Times

Science

Obama Seeking to Boost Study of Human Brain

By JOHN MARKOFF
Published: February 17, 2013

The Obama administration is planning a decade-long scientific effort to examine the workings of the human brain and build a comprehensive map of its activity, seeking to do for the brain what the Human Genome Project did for genetics.

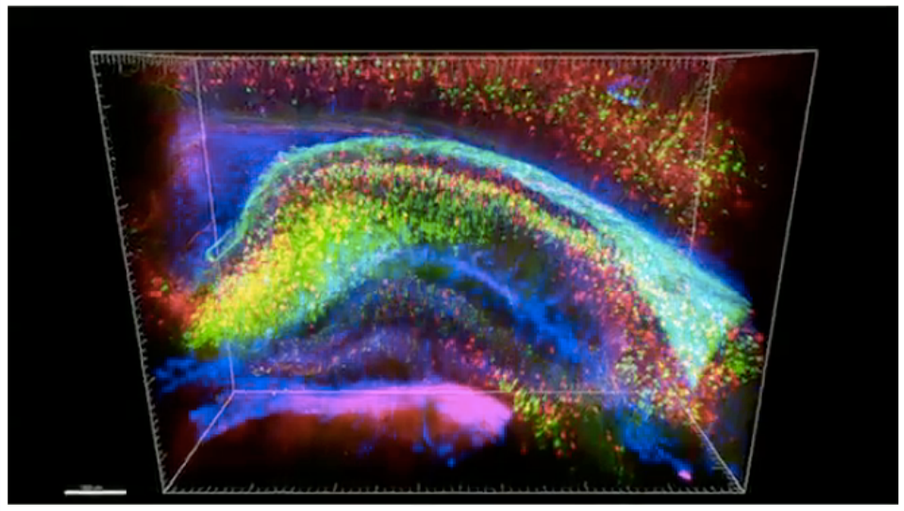
Enlarge This Image

Danny Moloshok/Reuters

Francis S. Collins, the director of the National Institutes of Health, one of the federal agencies involved in the project.

The project, which the administration has been looking to unveil as early as March, will include federal agencies, private foundations and teams of neuroscientists and nanoscientists in a concerted effort to advance the knowledge of the brain's billions of neurons and gain greater insights into perception, actions and, ultimately, consciousness.

Brains as Clear as Jell-O for Scientists to Explore



Kwanghun Chung and Karl Deisseroth/Stanford University

ScienceInsider
Breaking news and analysis from the world of science policy

Science
AAAS

Brain Project Draws Presidential Interest

by Emily Underwood and Jocelyn Kaiser on 20 February 2013, 2:00 PM | 6 Comments

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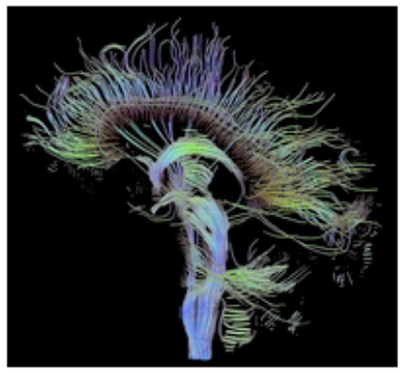
The New York Times on Monday revealed that the Obama administration will in its next budget proposal seek to launch a major research initiative, known as the Brain Activity Map (BAM) project, that could ultimately greatly expand our understanding of the healthy and diseased human brain. *Science*Insider takes a look at some of the many questions swirling around an effort that has already been compared to the Human Genome Project and could demand billions in research funding to accomplish.

ENLARGE IMAGE



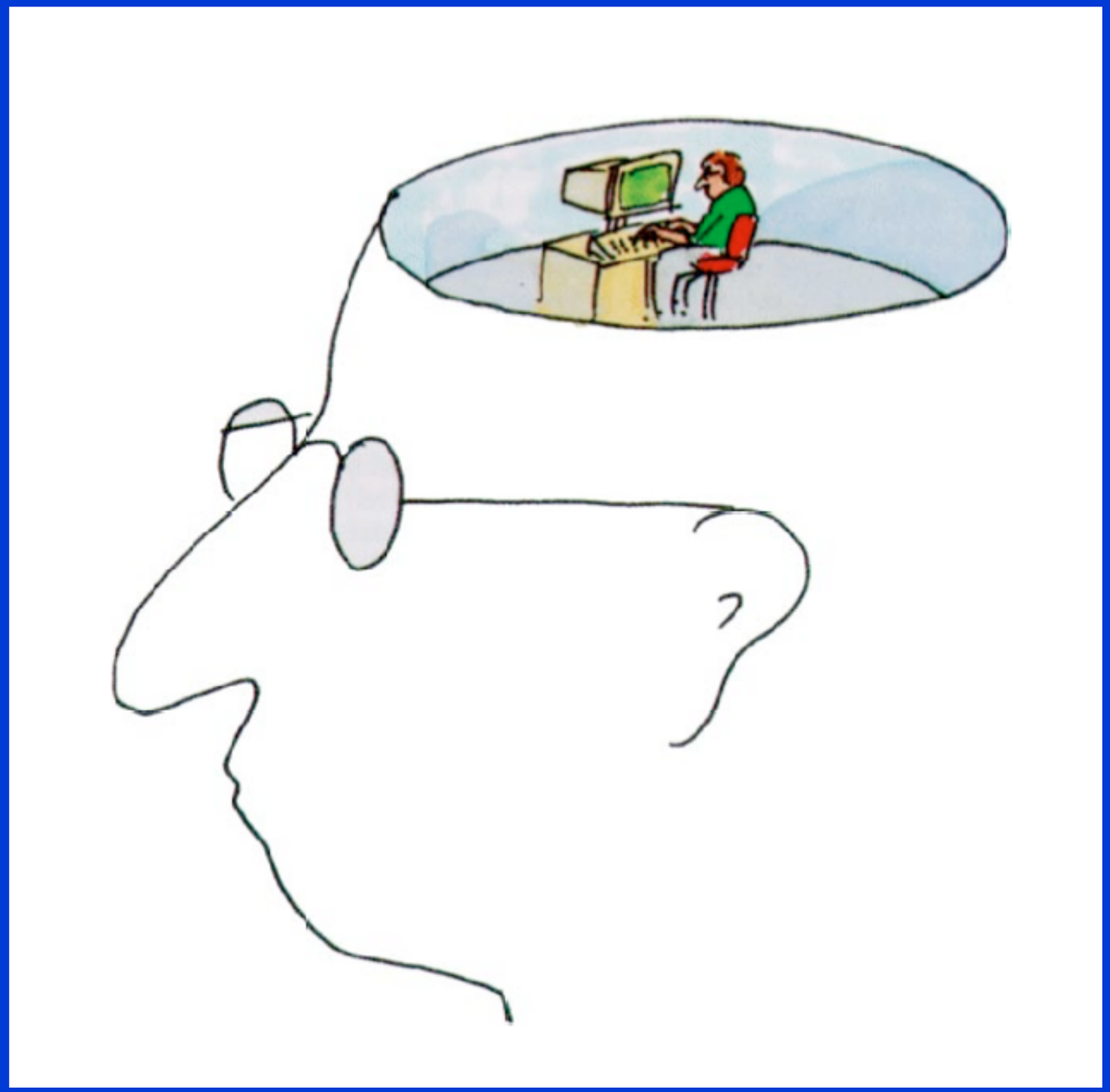
Hold that thought. Tools developed via the Brain Activity Map may monitor vast ensembles of neurons as they fire—bringing static maps of neural circuits to life (*shown above*).

Credit: Thomas Schultz/Creative Commons

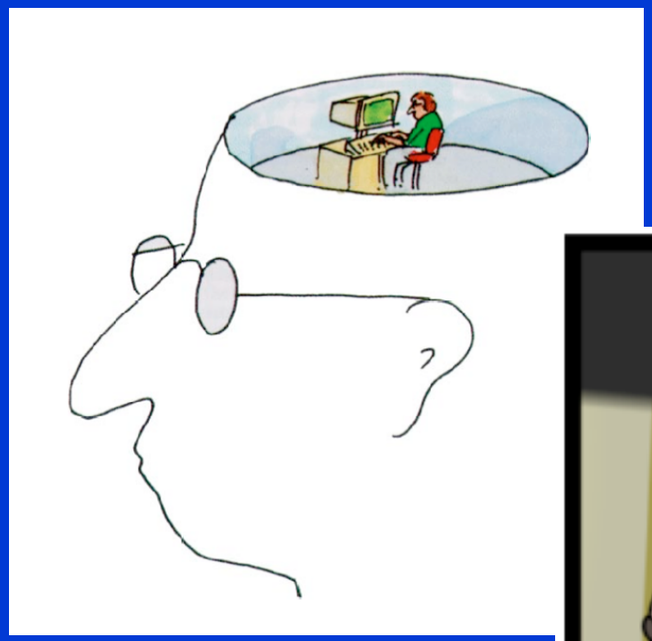
Q: What is a brain activity map?

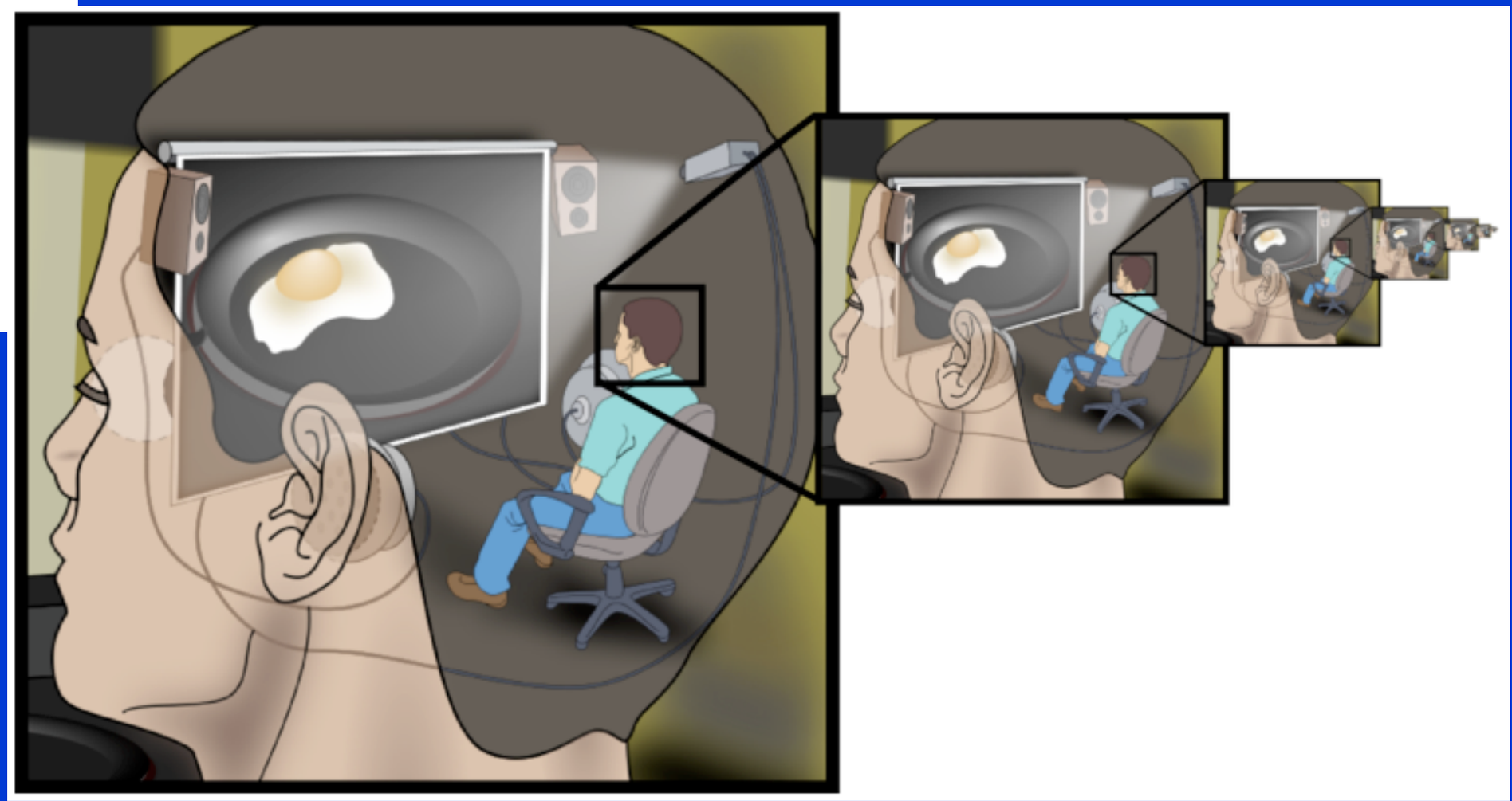
A: Neuroscientists arguably can only crudely measure the activity of a brain now. They can turn to PET and MRI imaging that detect "activation" of broad regions through proxies such as oxygen use, or they can measure the electrical activity of individual or small groups of neurons. Some neuroscientists compare the problem to getting the right resolution in a digital photograph or TV screen—PET and MRI lacks fine detail, producing "fuzzy" images, while focusing on small groups of neurons is like looking at a few pixels up close, losing sight of the bigger picture. Researchers generally agree that critical brain functions such as thought and perception happen somewhere between these two extremes, involving anywhere from a few thousand to millions of neurons. Now, researchers can't monitor such large ensembles of neurons; to produce a brain activity map for humans will require developing new tools that can image and track an enormous number of cells in animal models, then finding a way to use those tools safely in humans. It's not clear yet what states of brain activity the proposed project would eventually map, but theoretically, such tools could help scientists understand what goes wrong in disorders, such as epilepsy and schizophrenia, that are suspected to originate from abnormal neural connections between different brain areas.

Some People Think They Know How the Brain Works...



But This is Just an Example of the "Humuncular Fallacy"





A "Multi-Plex Cinema" Version of Dennett's "Cartesian Theater"

How Does a Computer "Compute"?

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

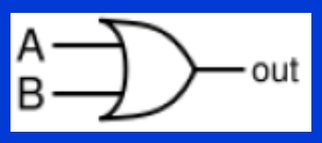
Logic Gates in Digital (Von Neumann / Turing) Computers

AND

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

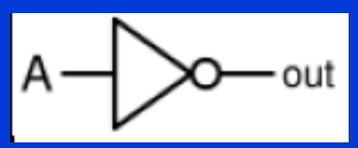
OR

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



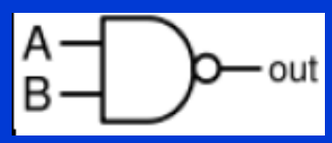
NOT

INPUT	OUTPUT
A	NOT A
0	1
1	0



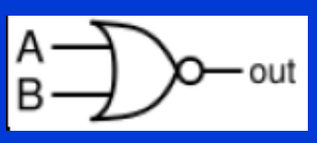
NAND

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



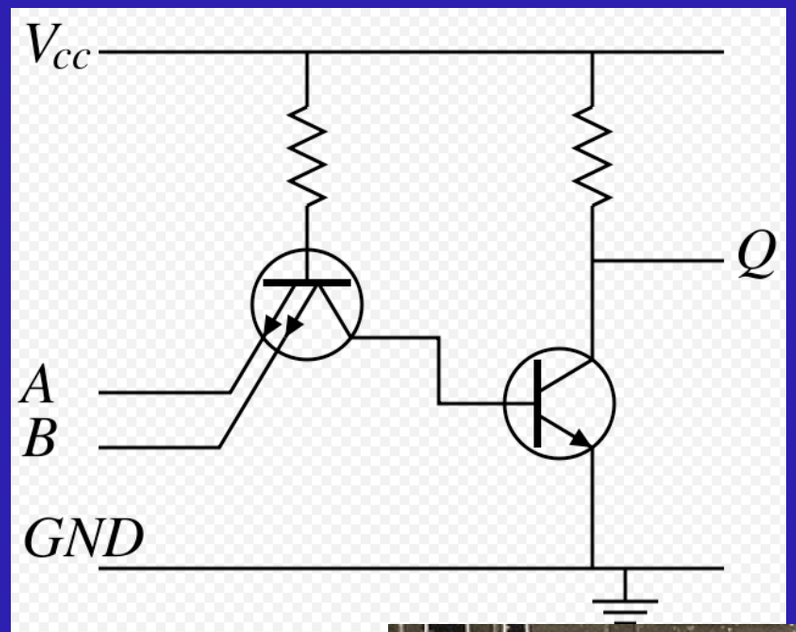
Together, these logical operations implement

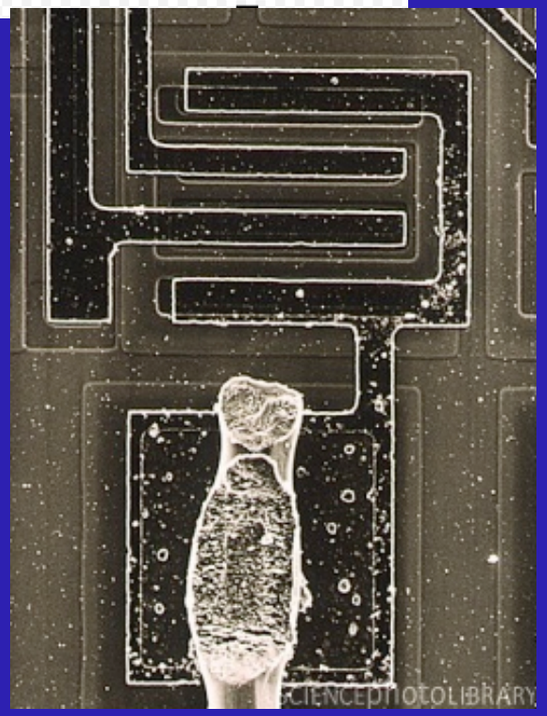
Two Key *"Computational Primitives"* for Digital Computation:

Boolean Logic and Binary Arithmetic

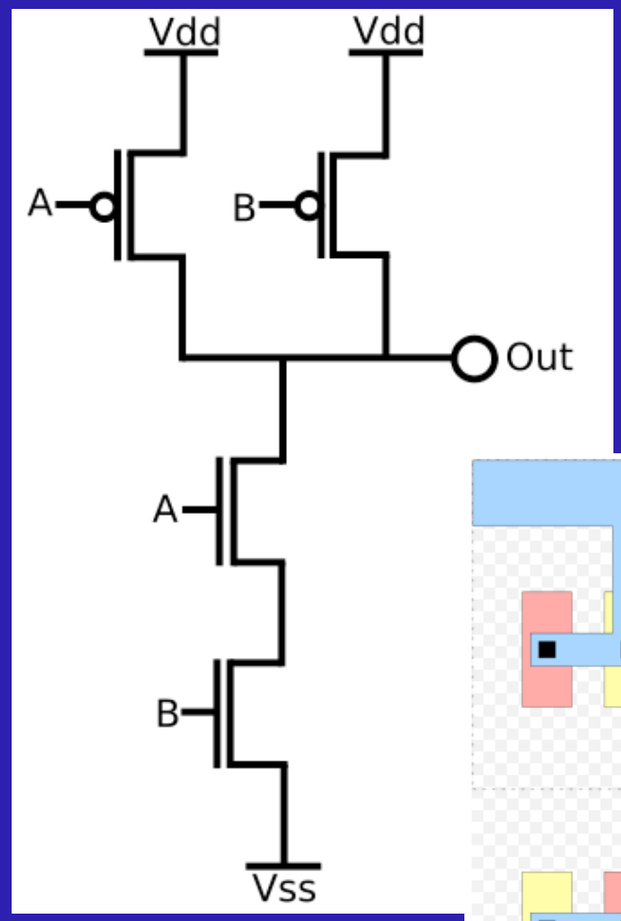
Two Different Physical Implementations of the Same NAND (Negated AND) Gate

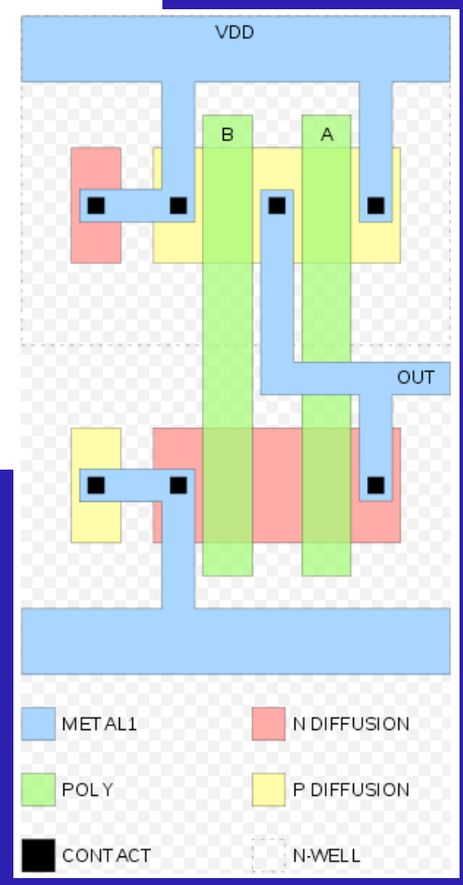
NAND Gate in TTL Logic





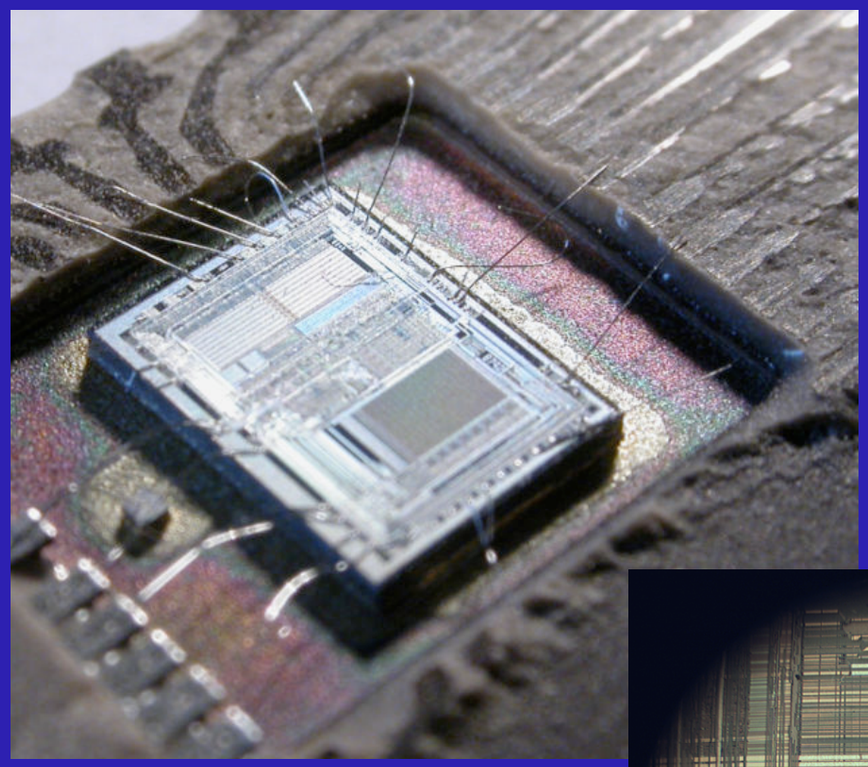
NAND Gate in CMOS Logic

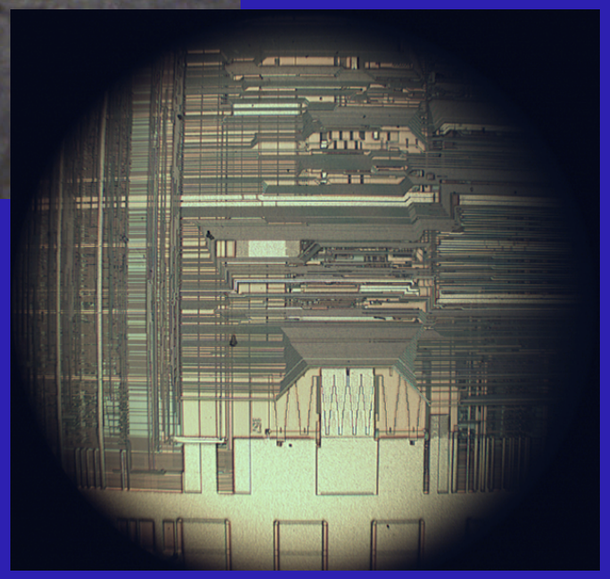




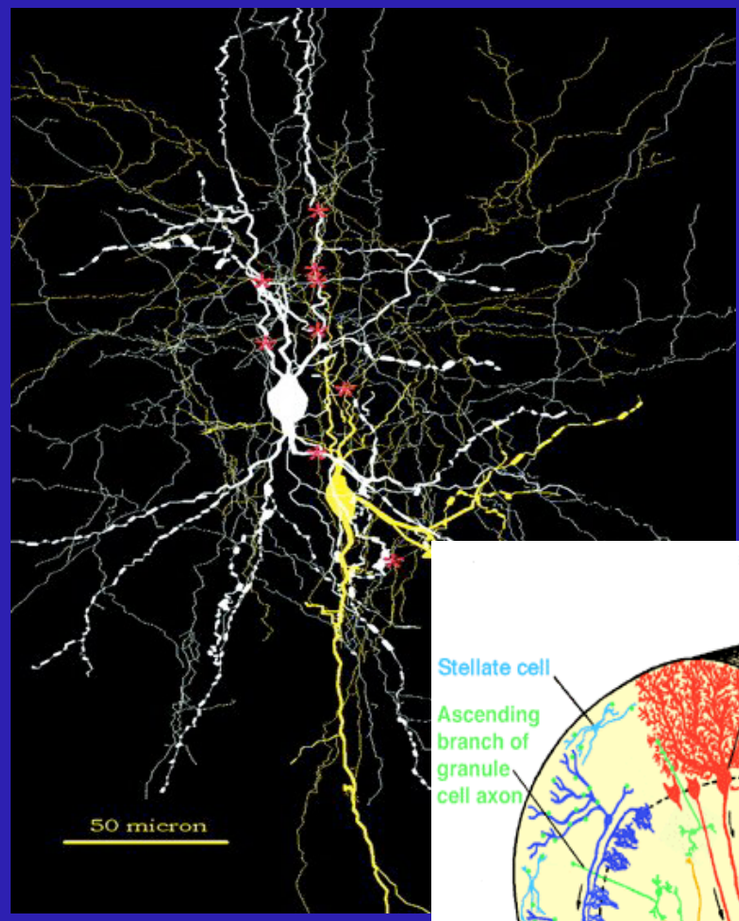
Distinction Between the Abstract "Computational Level" and the Physical Substrate

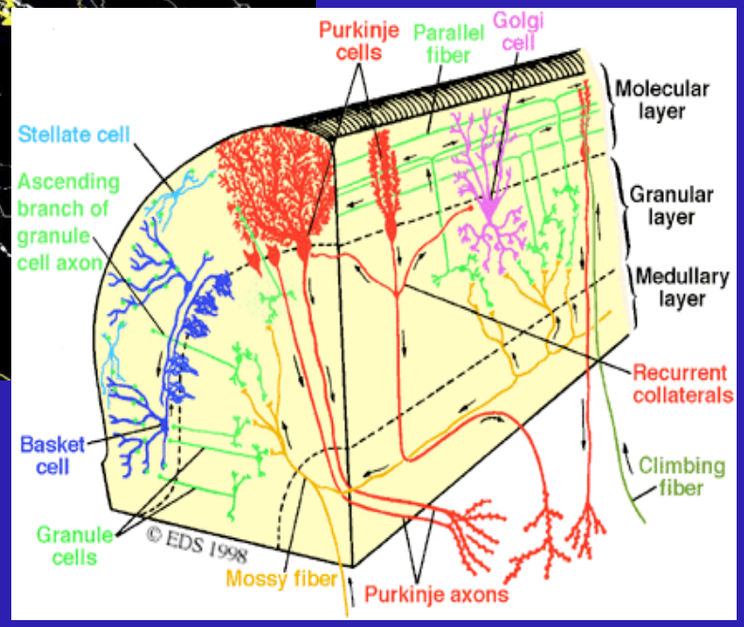
Logic Gates in Digital (Von Neumann / Turing) Machines



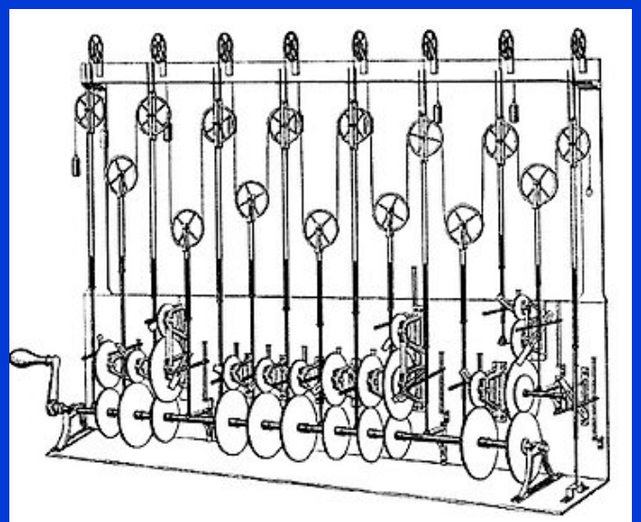


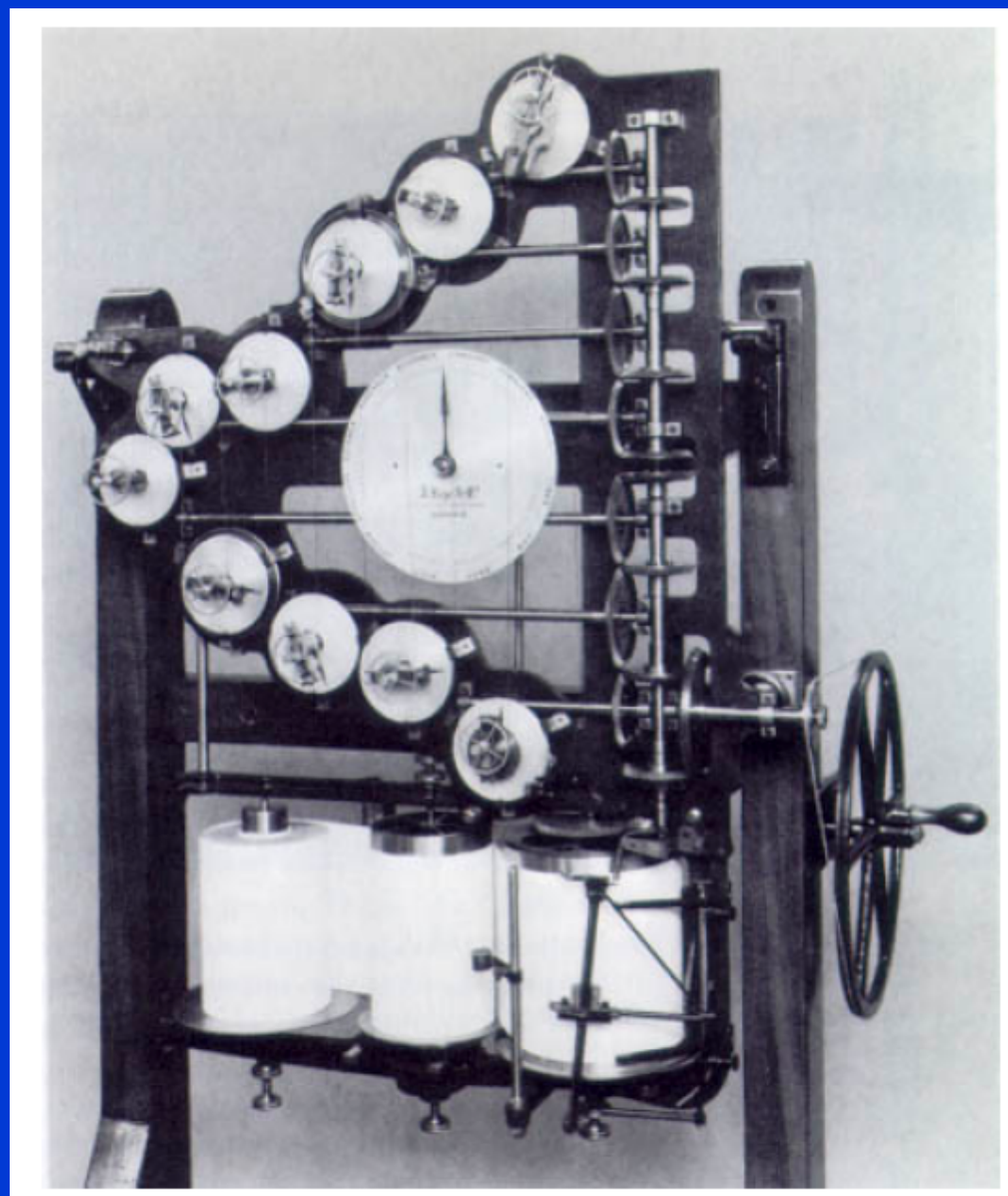
Is There an Analogous Abstraction for Neurons and Brains?



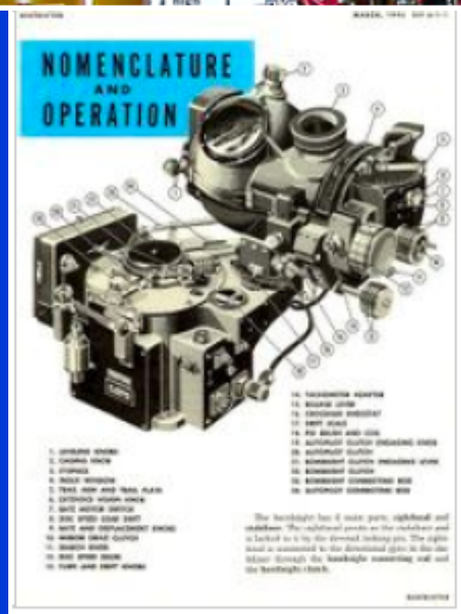


Analog Computation: A Rich but Under-Explored Alternative to Digital Computation (for very good reasons...) and Likely a Fertile Metaphor for Neural "Computation"



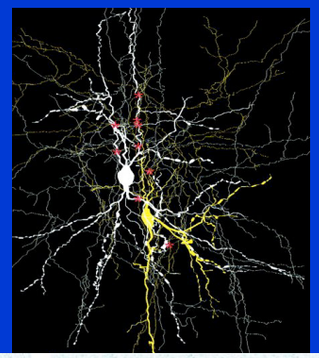


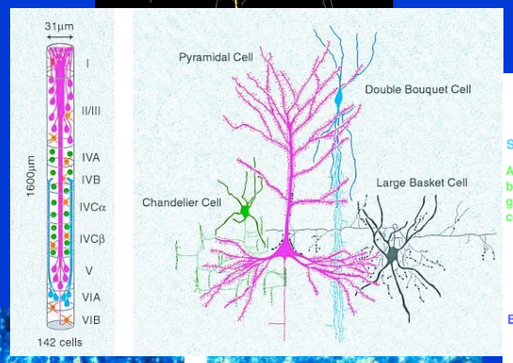
Kelvin's Tide Predictor (1876-1878)

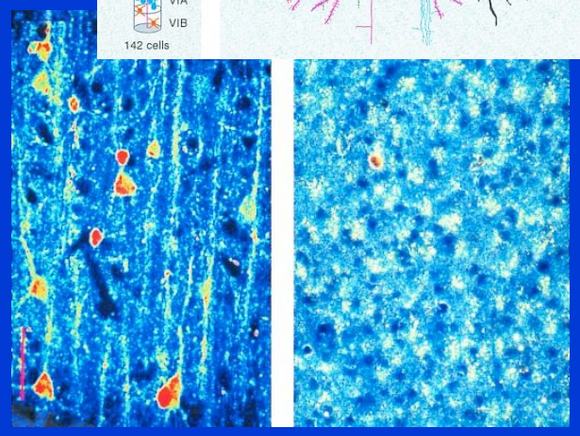


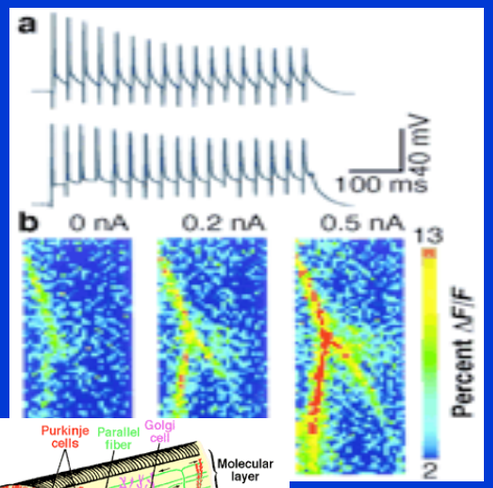
A page from the *Bombardier's Information File* (BIF) that describes the components and controls of the Norden bombsight. The **Norden bombsight** was a highly sophisticated optical/mechanical analog computer used by the United States Army Air Force during World War II, the Korean War, and the Vietnam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

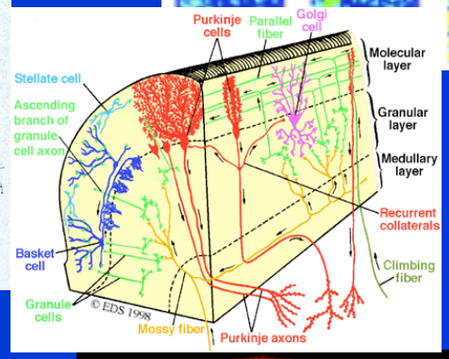
Are There Analogous "Computational Primitives" for the Brain?

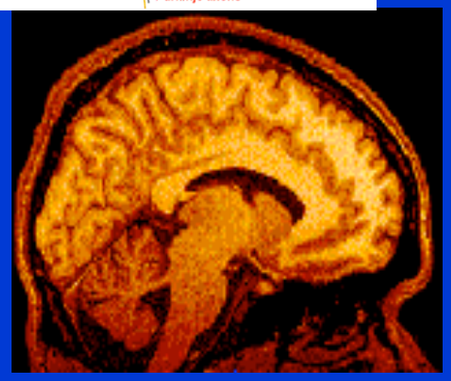












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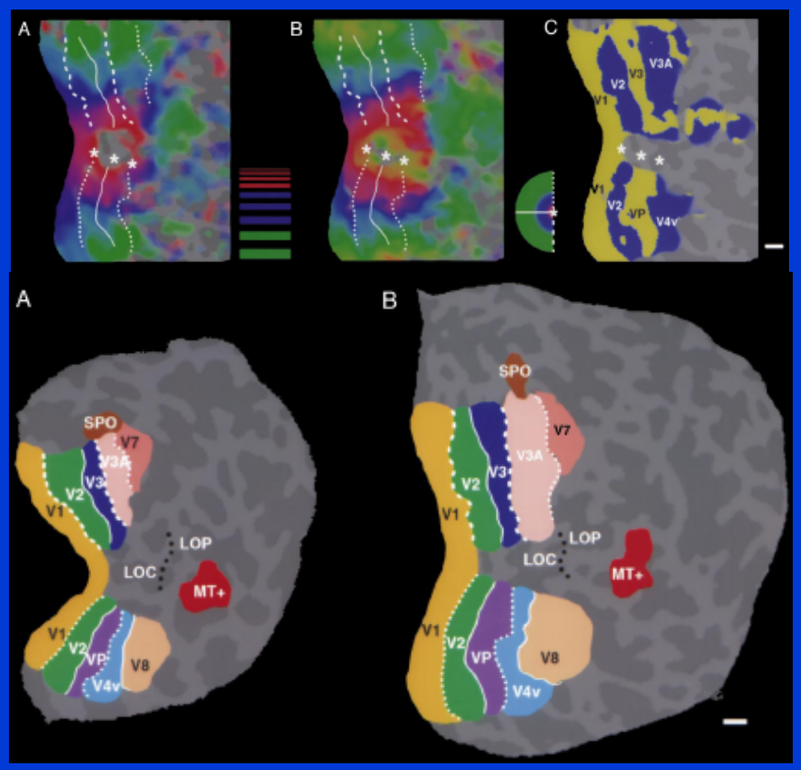
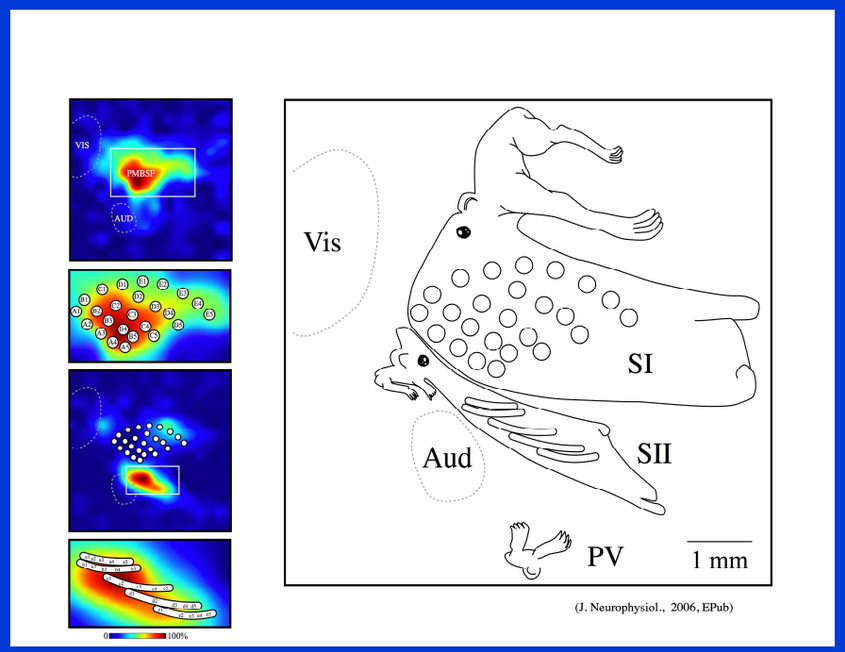
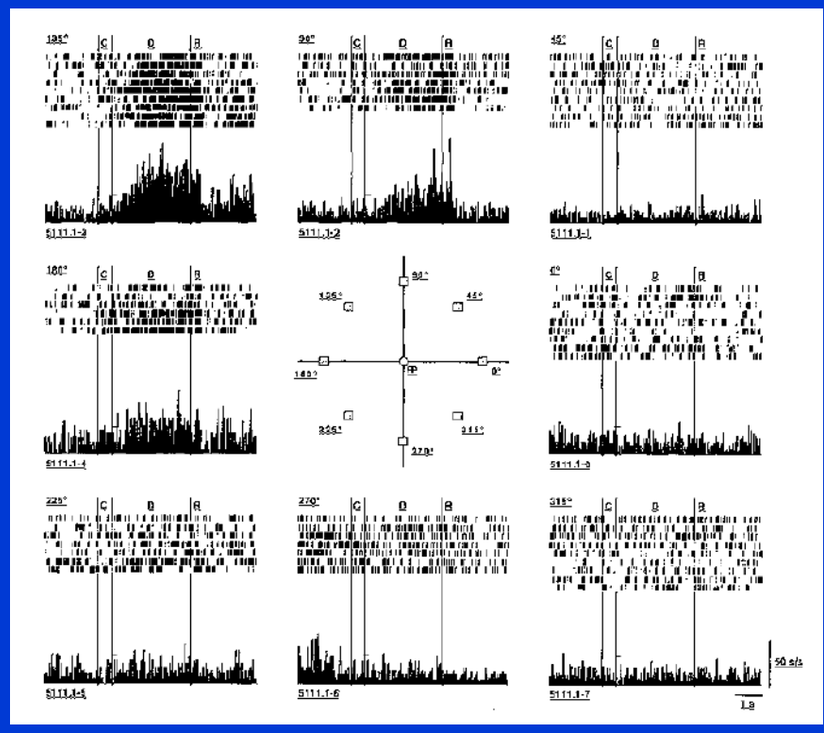
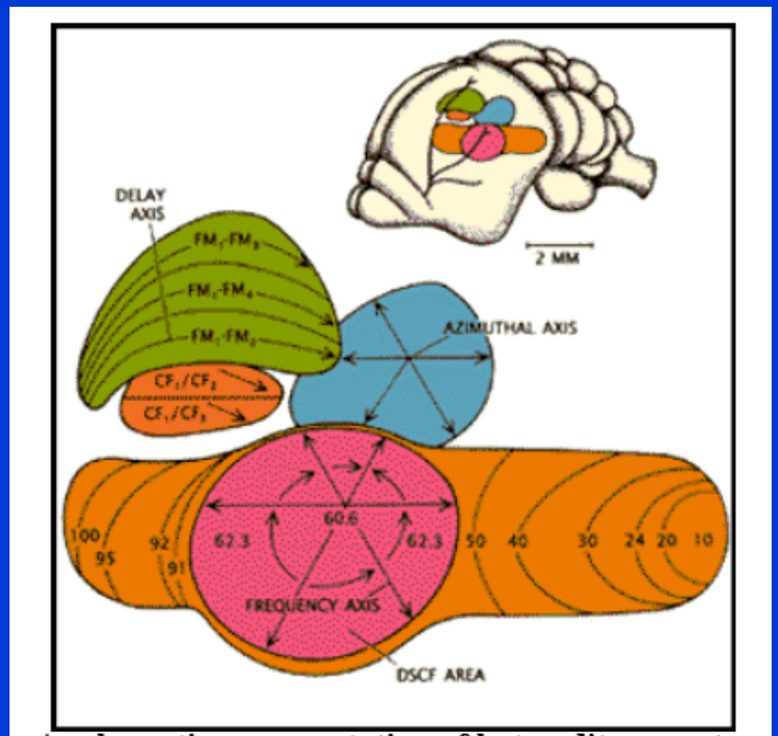
Candidate “Computational Primitives” for the Brain: 1. Topographic Representations and Transformations?



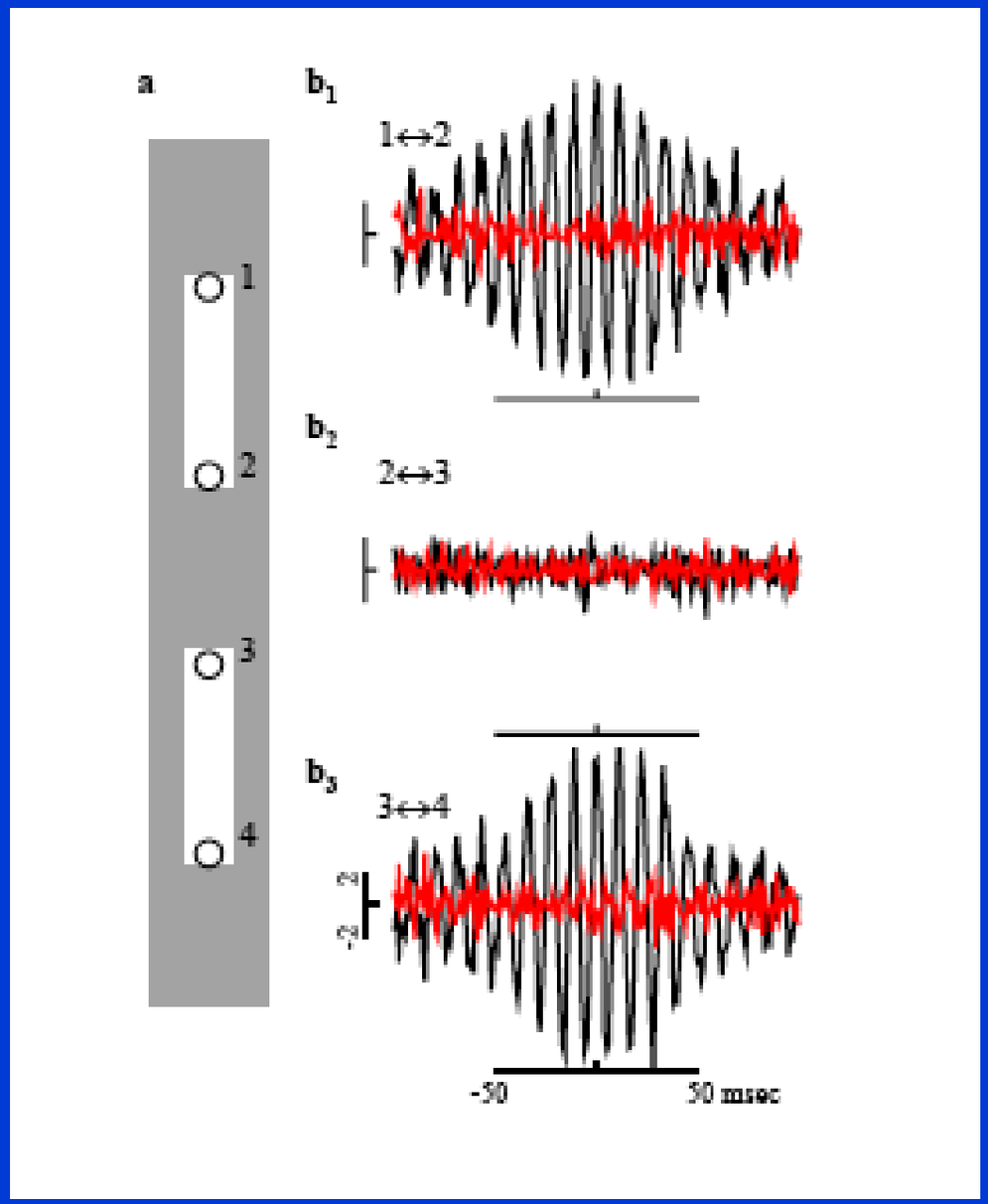


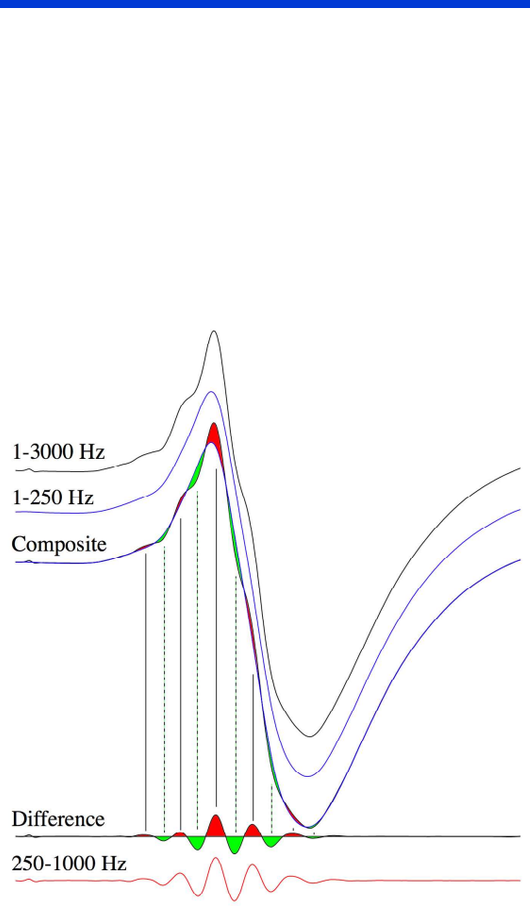


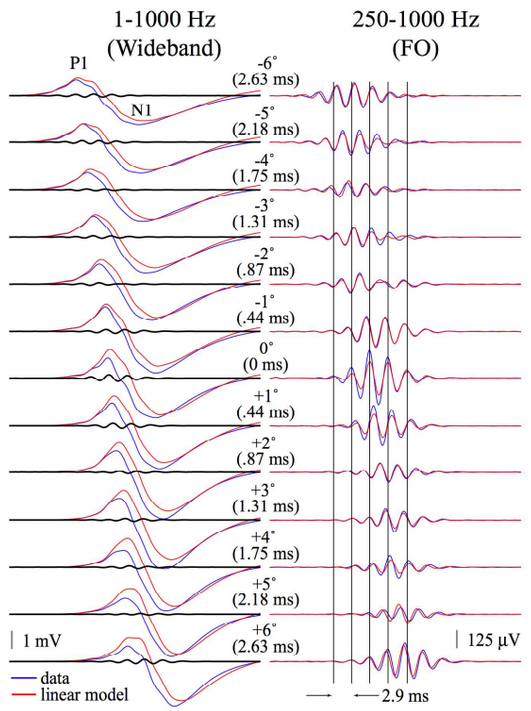


A schematic representation of bat auditory cortex

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

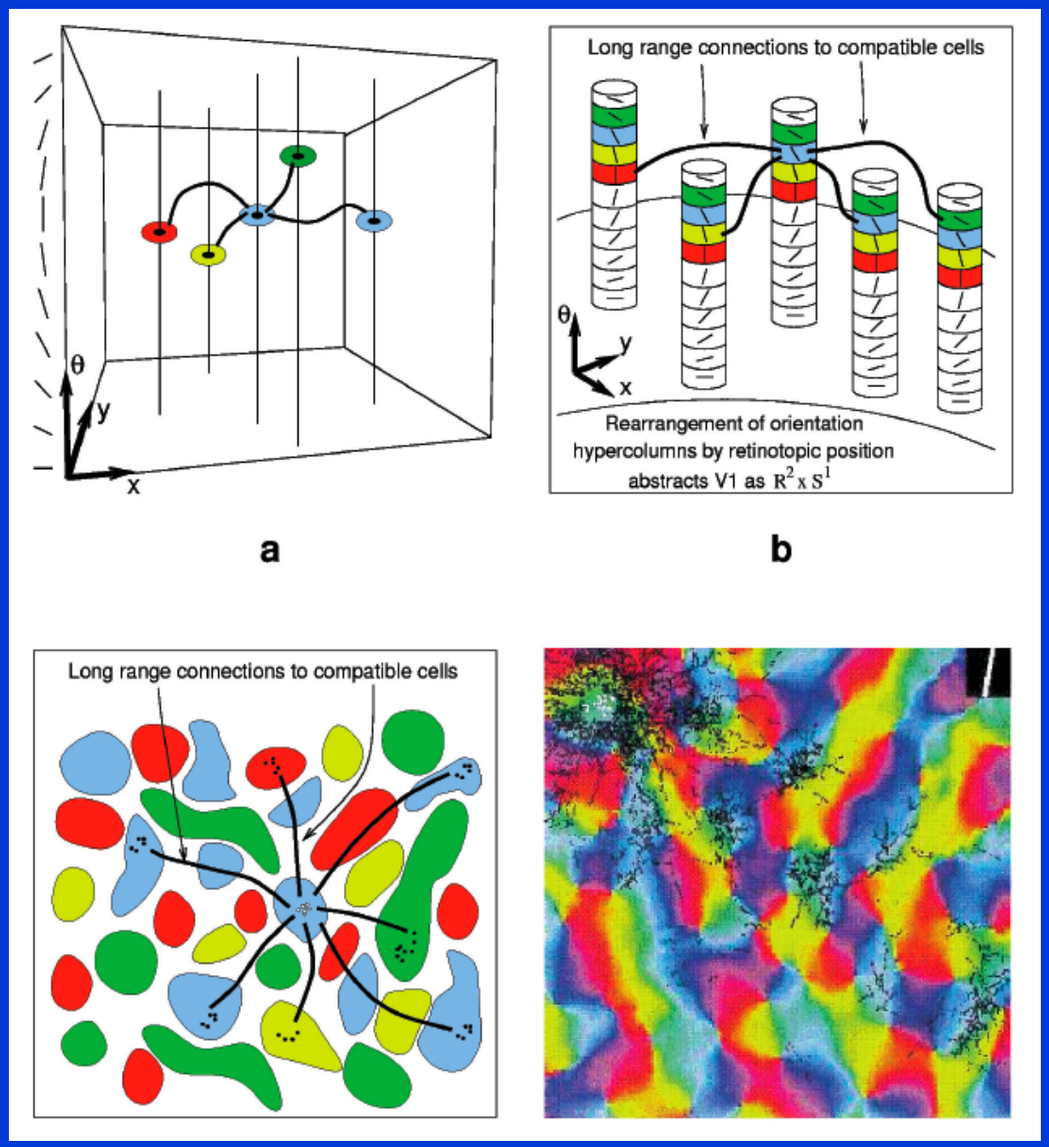


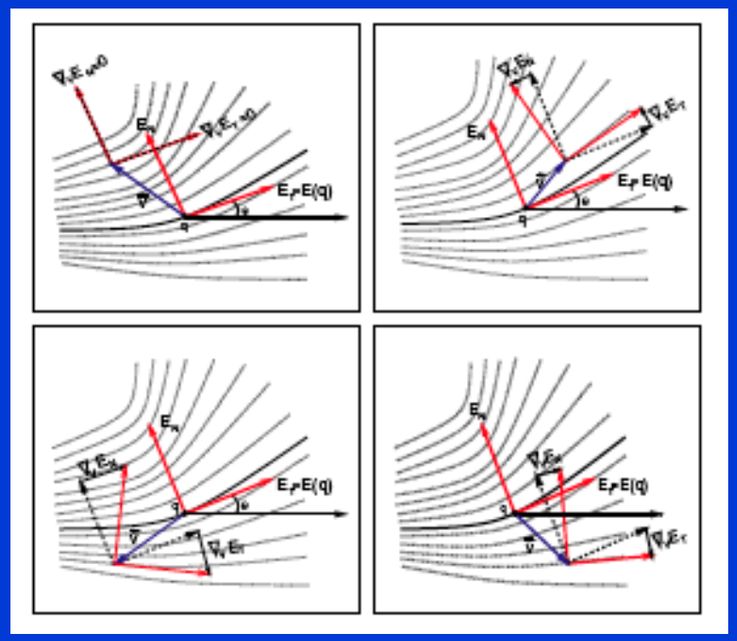


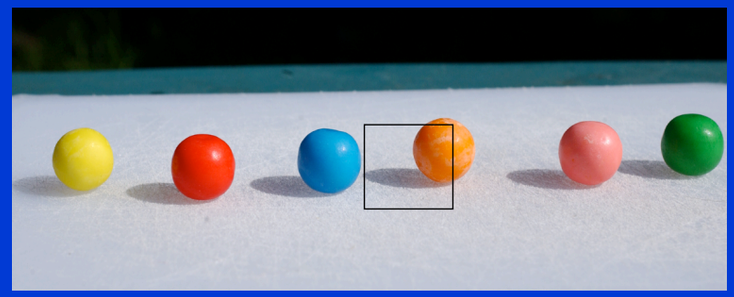


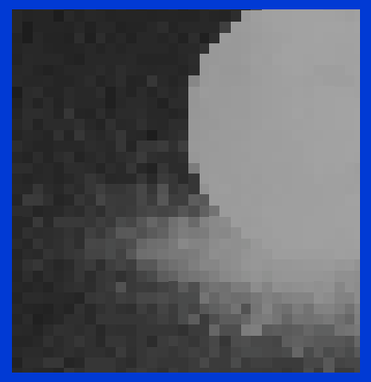
(J. Neurophysiol., 2006, EPub)

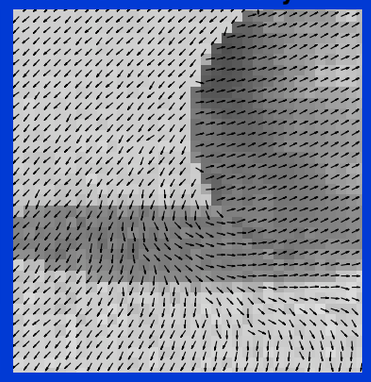
Candidate “Computational Primitives” for the Brain:
3. Differential Geometry (Zucker et al.)



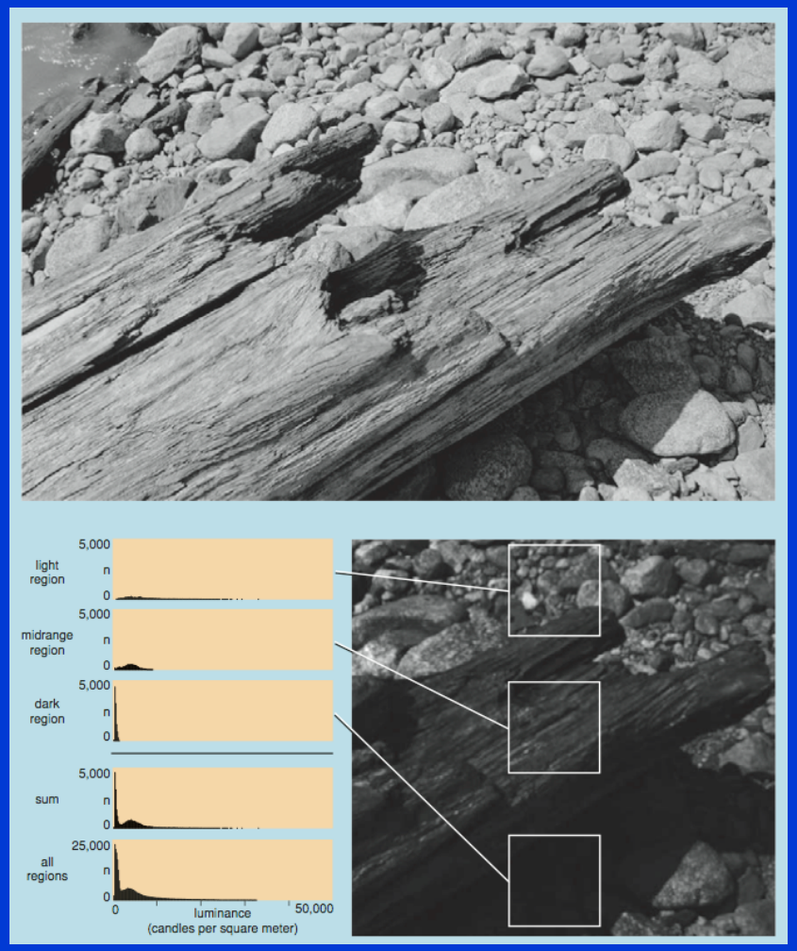


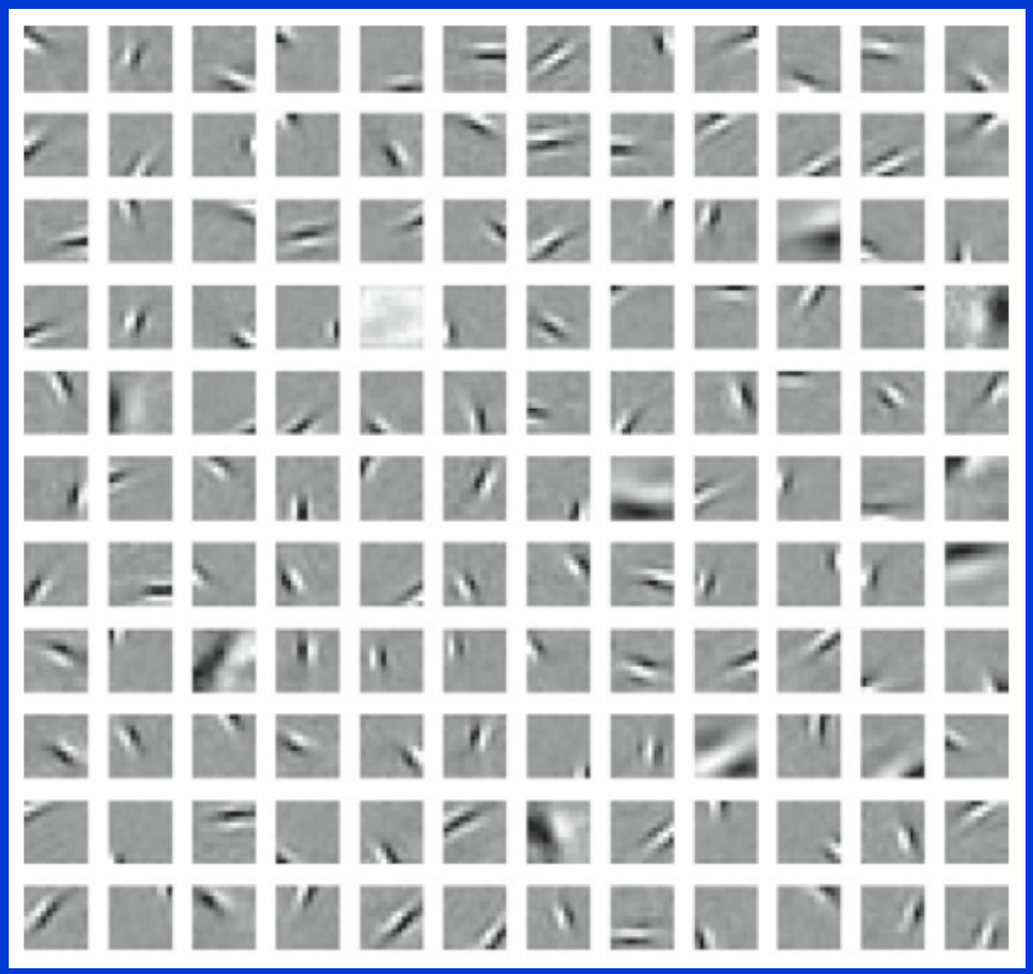


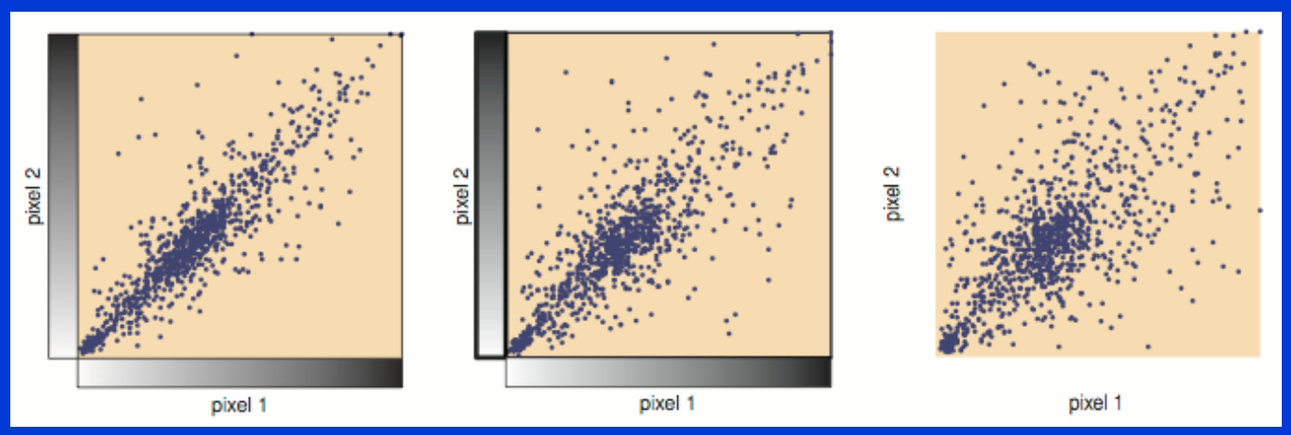




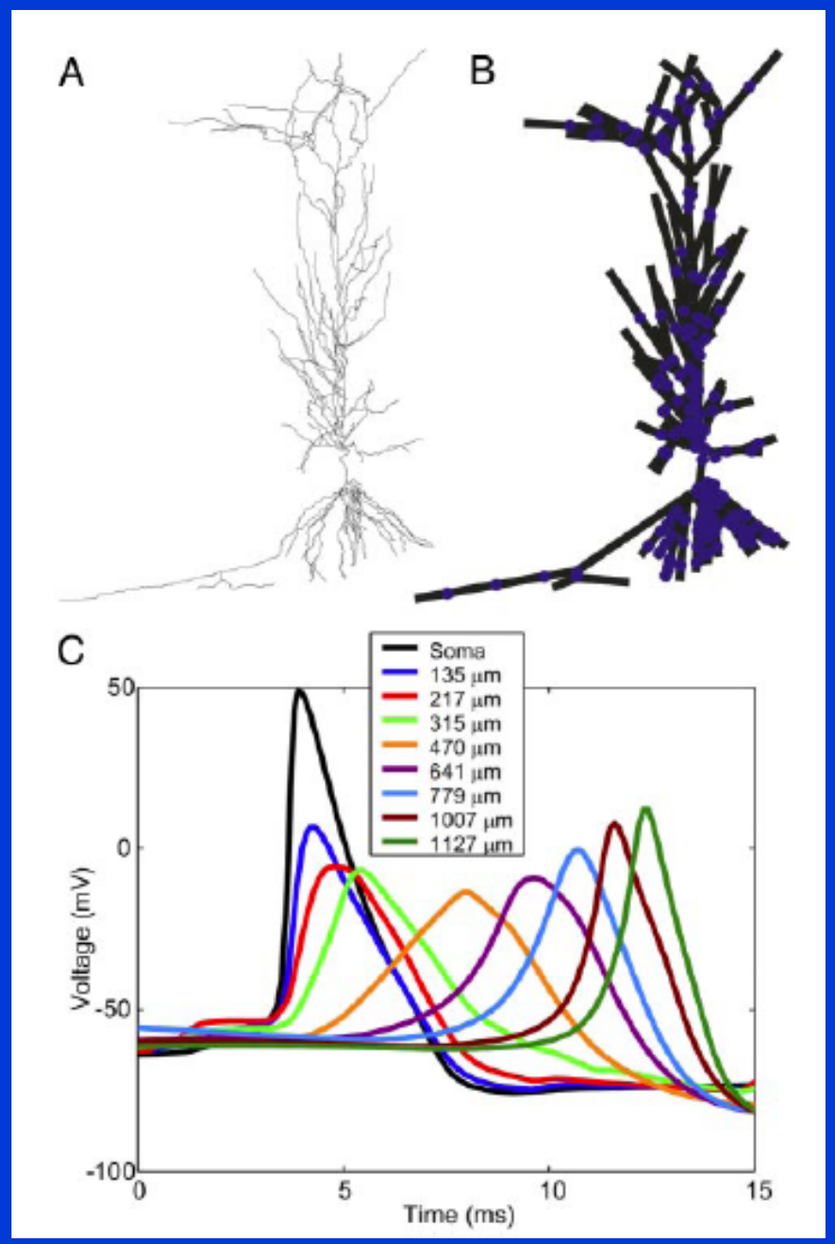
Candidate “Computational Primitives” for the Brain: 4. Statistics of Visual Images and “Sparse Coding”?







Candidate "Computational Primitives" for the Brain: 5. Hebbian Synapses and Spike-Timing Dependent Plasticity?



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Candidate “Computational Primitives” for the Brain: Don’t Rule Out the Possibility of New Physical Mechanisms

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Neurobiologists Find that Weak Electrical Fields in the Brain Help Neurons Fire Together

Coordinated behavior occurs whether or not neurons are actually connected via synapses

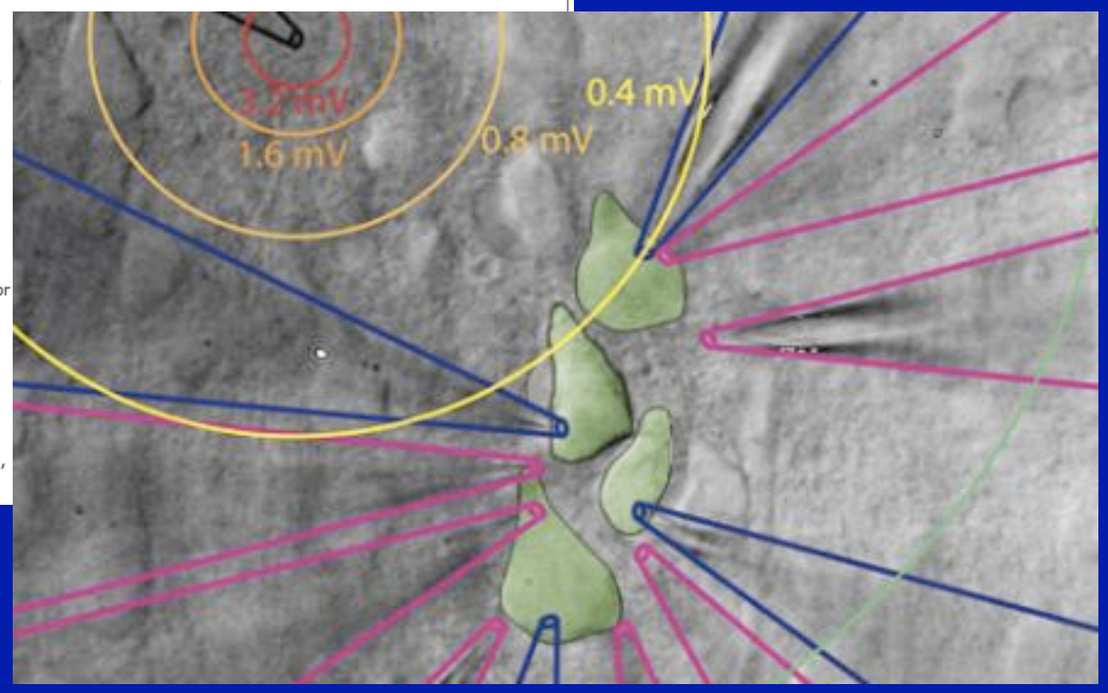
Pasadena, Calif.—The brain—awake and sleeping—is awash in electrical activity, and not just from the individual pings of single neurons communicating with each other. In fact, the brain is enveloped in countless overlapping electric fields, generated by the neural circuits of scores of communicating neurons. The fields were once thought to be an "epiphenomenon" similar to the sound the heart makes—which is useful to the cardiologist diagnosing a faulty heart beat, but doesn't serve any purpose to the body, says Christof Koch, the Lois and Victor Troendle Professor of Cognitive and Behavioral Biology and professor of computation and neural systems at the California Institute of Technology (Caltech).

New work by Koch and neuroscientist Costas Anastassiou, a postdoctoral scholar in biology, and his colleagues, however, suggests that the fields do much more—and that they may, in fact, represent an additional form of neural communication.

"In other words," says Anastassiou, the lead author of a paper about the work appearing in the journal *Nature Neuroscience*, "while active neurons give rise to extracellular fields, the same fields feed back to the neurons and alter their behavior," even though the neurons are not physically connected—a phenomenon known as ephaptic (or field) coupling. "So far, neural communication has been thought to occur almost entirely via traffic involving synapses, the junctions where one neuron connects to the next one. Our work suggests an additional means of neural communication through the extracellular space independent of synapses."

Extracellular electric fields exist throughout the living brain. Their distant echoes can be measured outside the skull as EEG waves. These fields are particularly strong and robustly repetitive in specific brain regions such as the hippocampus, which is involved in memory formation, and the neocortex, the area where long-term memories are held. "The perpetual fluctuations of these extracellular fields are the hallmark of the living and behaving brain in all organisms, and their absence is a strong indicator of a deeply comatose, or even dead, brain," Anastassiou explains.

Previously, neurobiologists assumed that the fields were capable of affecting—and even controlling—neural activity only during severe pathological conditions such as epileptic seizures, which induce very strong fields. Few studies,



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Conclusions: What Kind of Computer is the Brain?

Um, er, well, to tell the truth, we don't really know in detail (yet), but we do know:

1. It is likely that the brain has its own "computational primitives" very different from the binary arithmetic and Boolean algebra that are the computational primitives for digital computers.

2. It will be essential to distinguish between abstract computational levels and the physical substrates of the brain.

3. It is unlikely that focus on the physical substrate alone will yield success, any more than observing processor bits in a computer with an oscilloscope will enable us to understand the difference between, say, a web browser and Excel. The differences are at a more abstract level.

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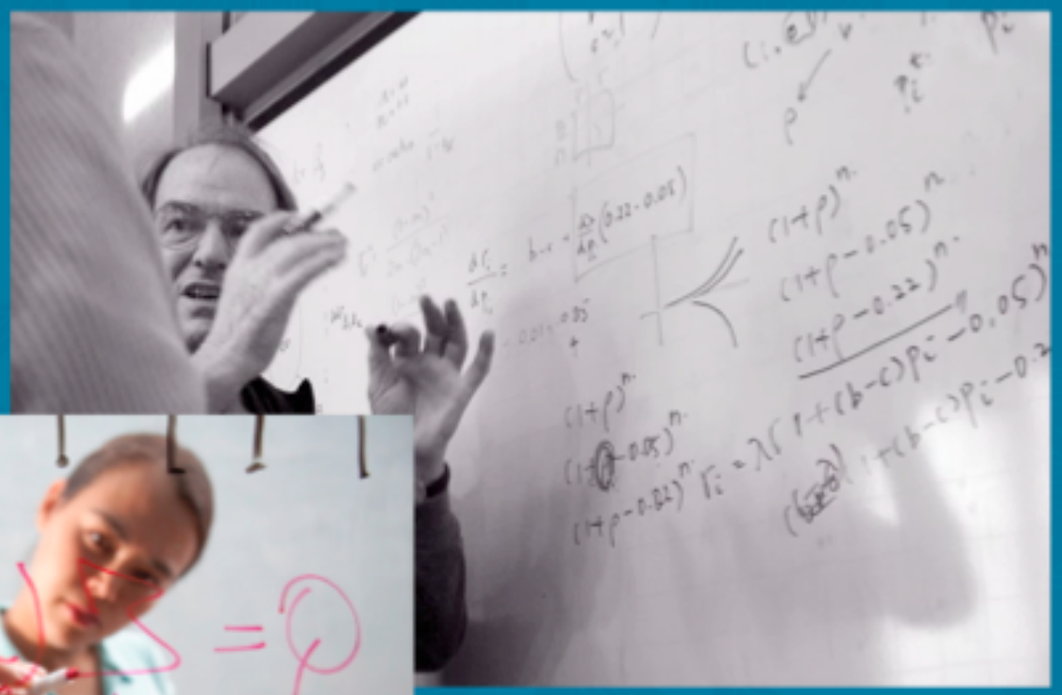
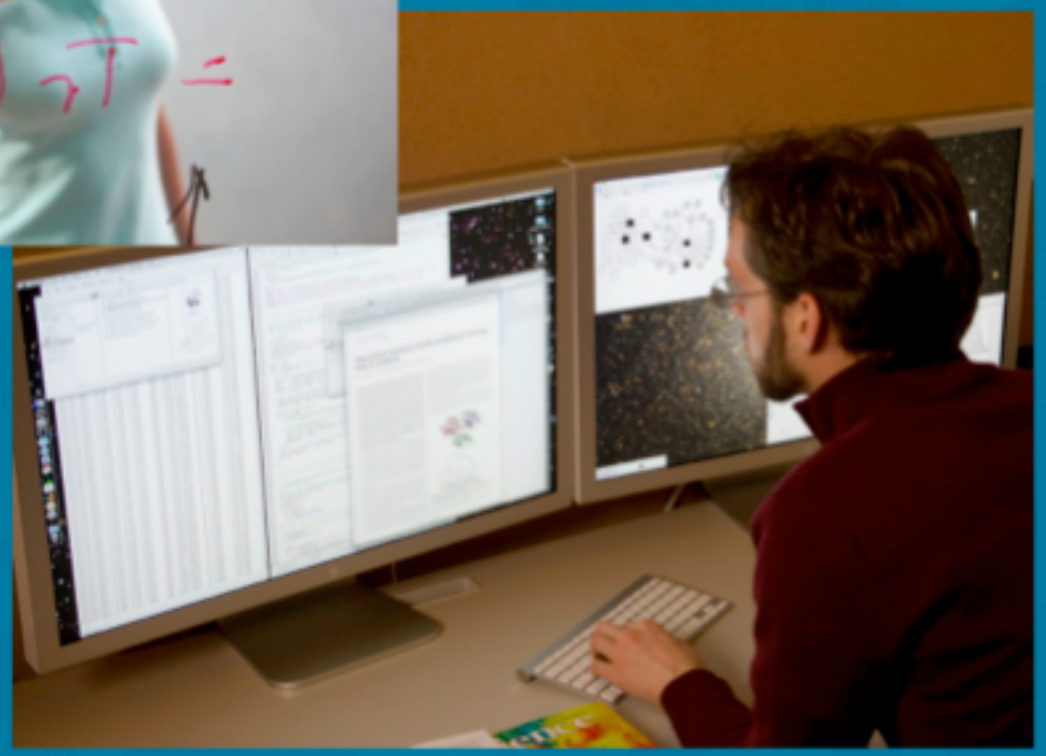
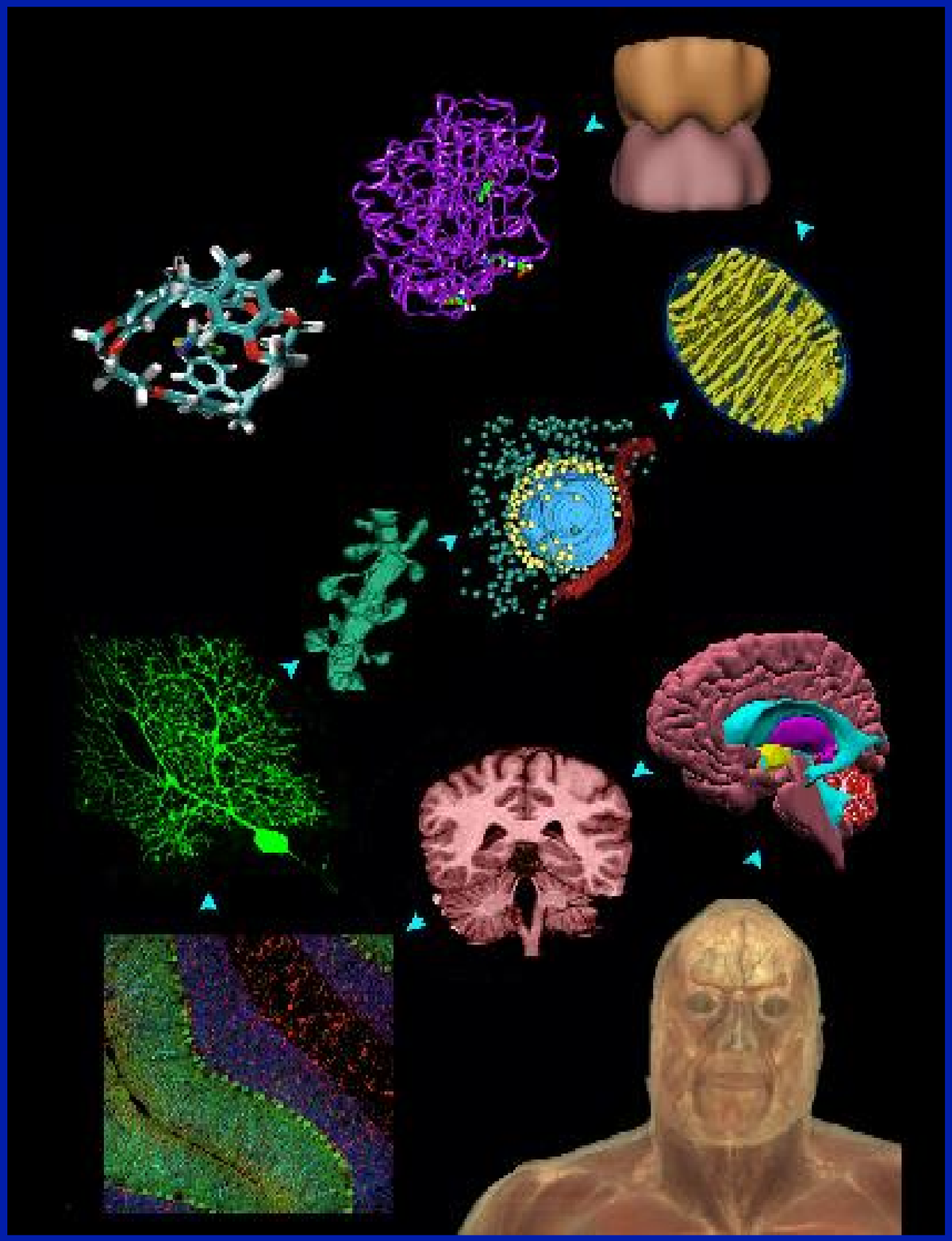
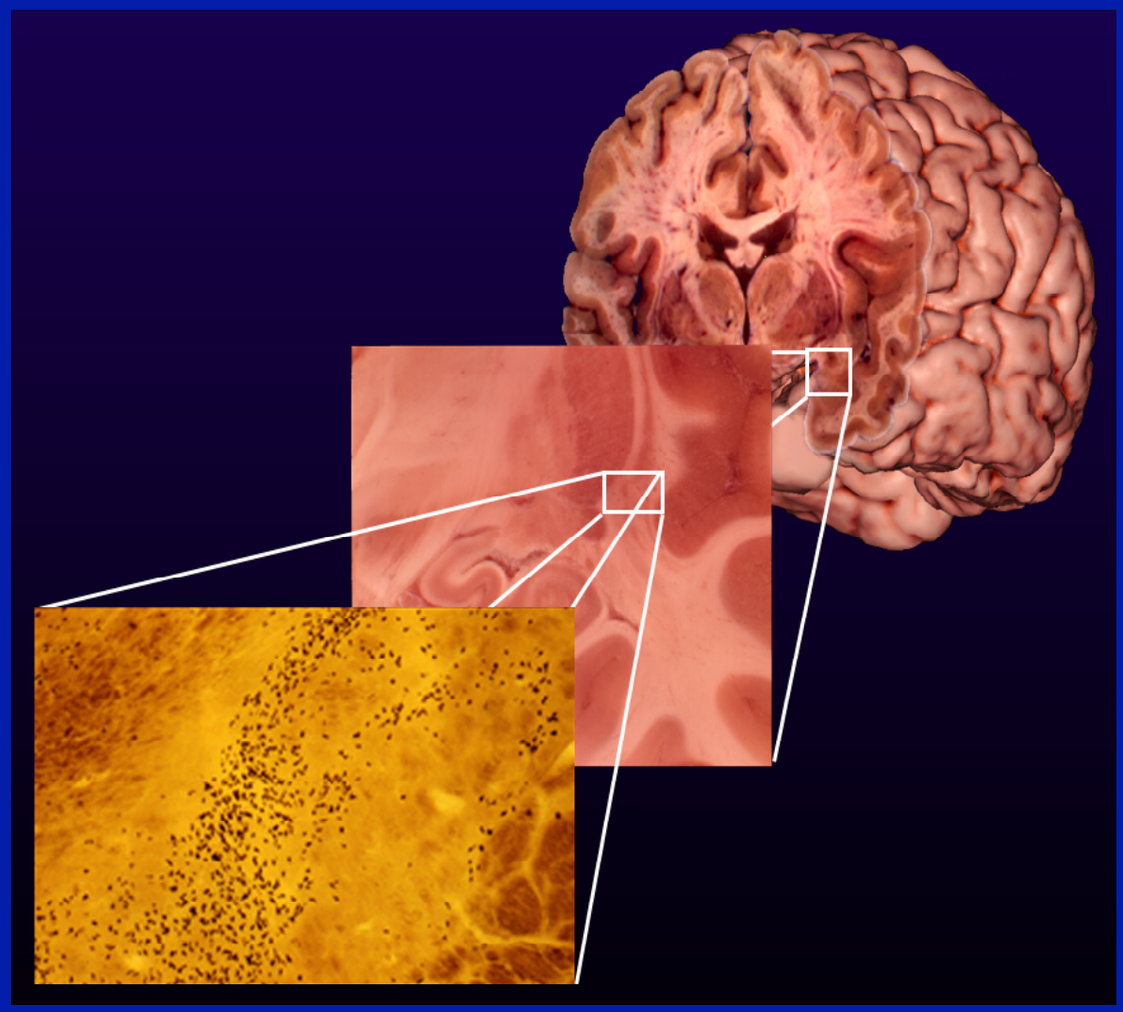




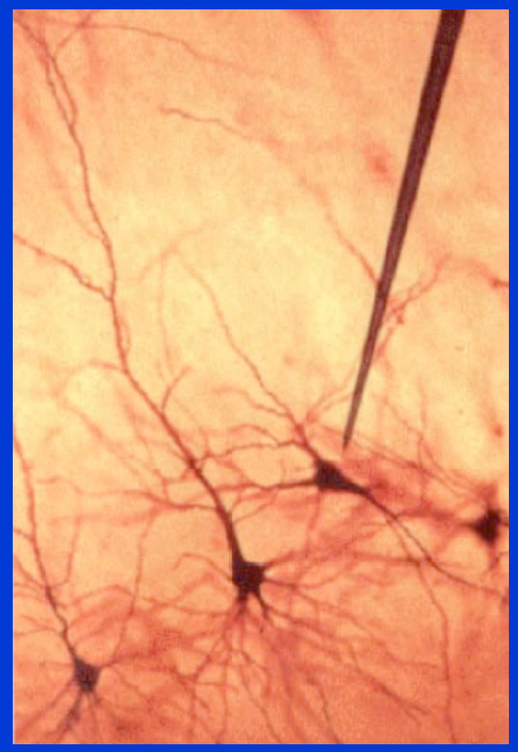
The Brain as a Network: Hierarchical Oganization is Fundamental

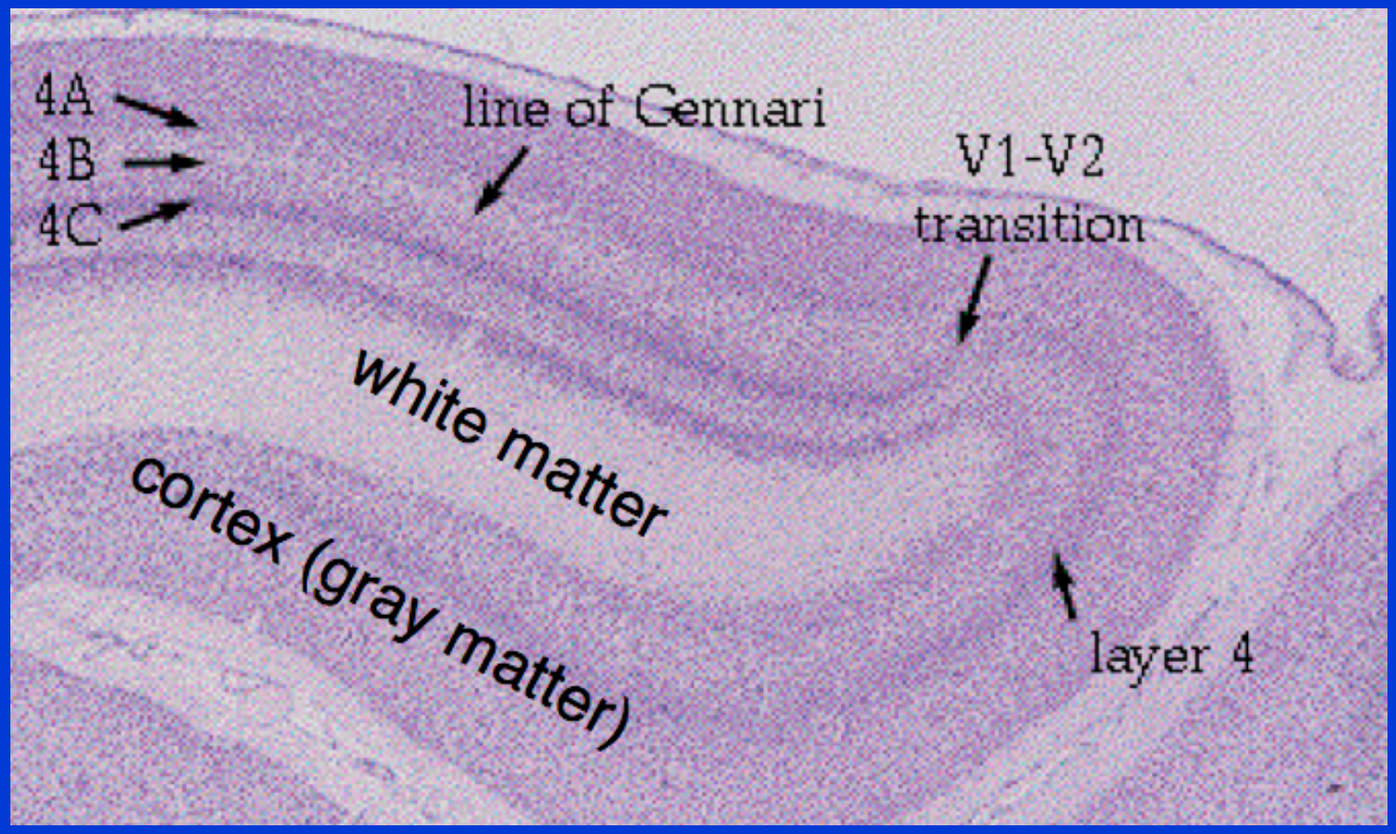


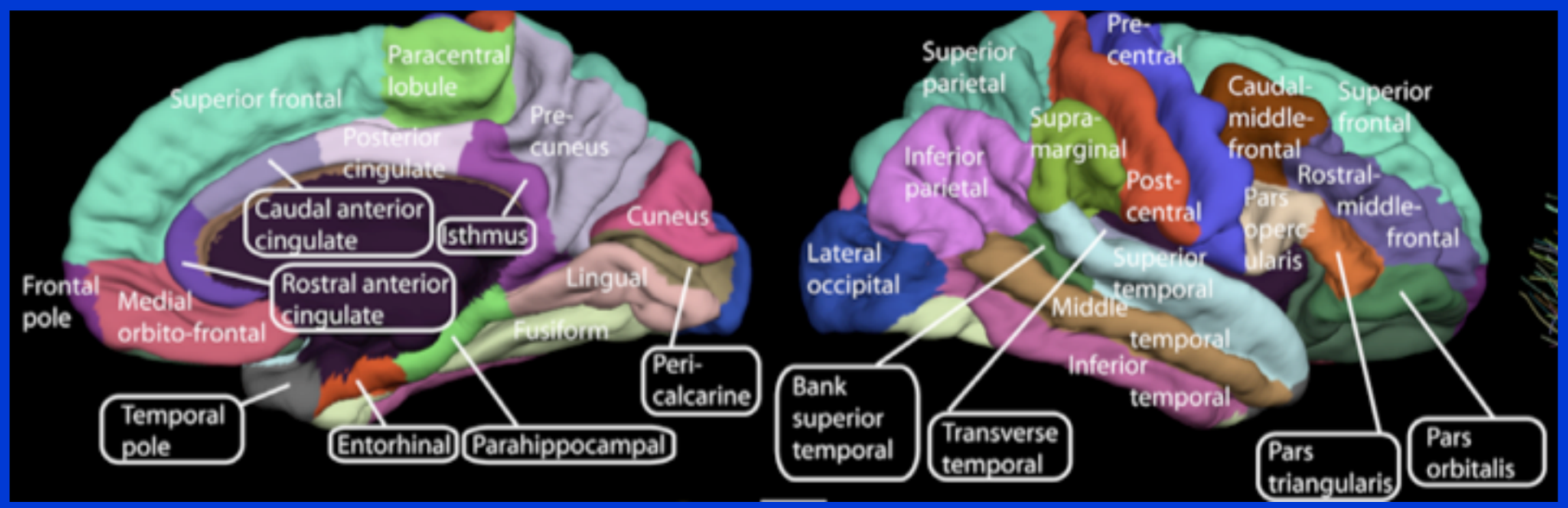


Martone, Ellisman, Toga et al., UCSD, UCLA

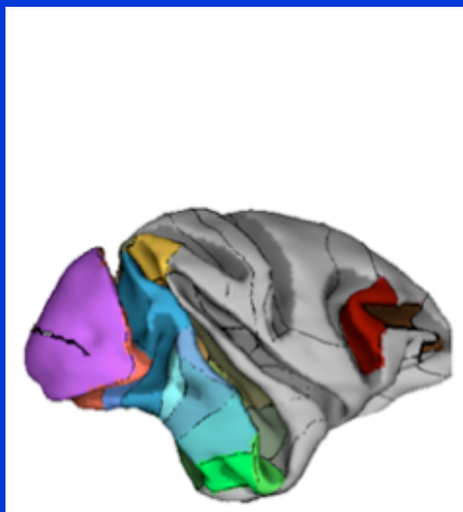
The Brain as a Network: (1) From Individual Neurons to Regional Structures

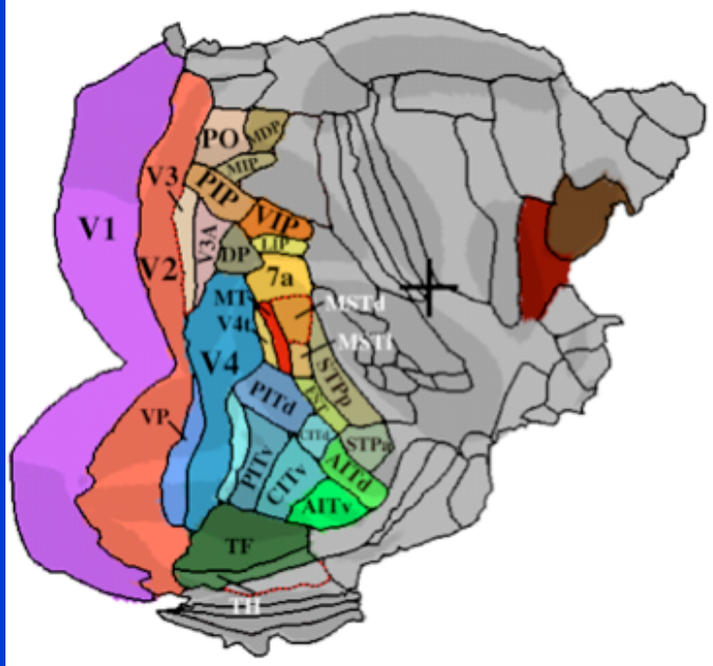


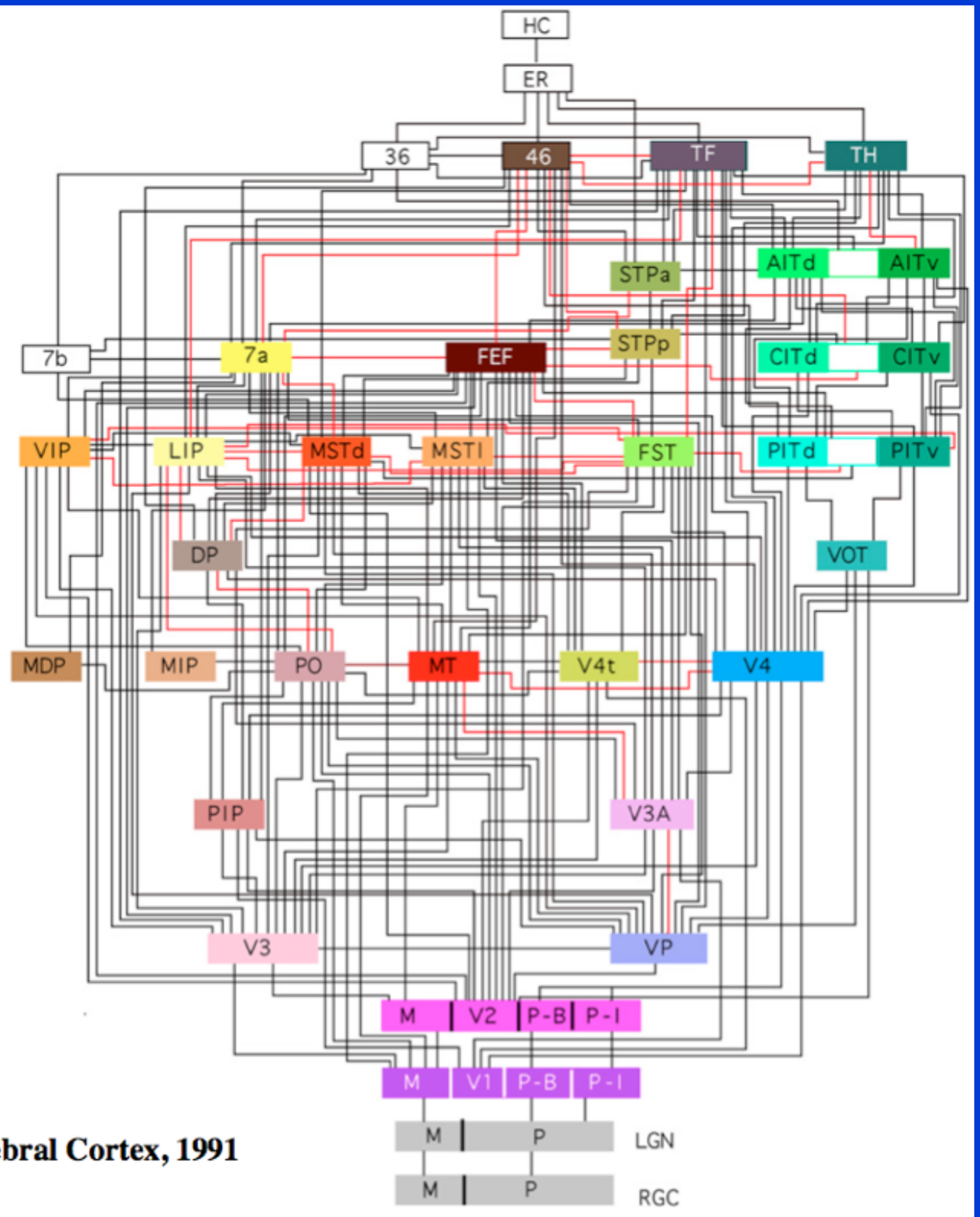




The Brain as a Network: (2) Regional Structures in Monkey Visual Cortex

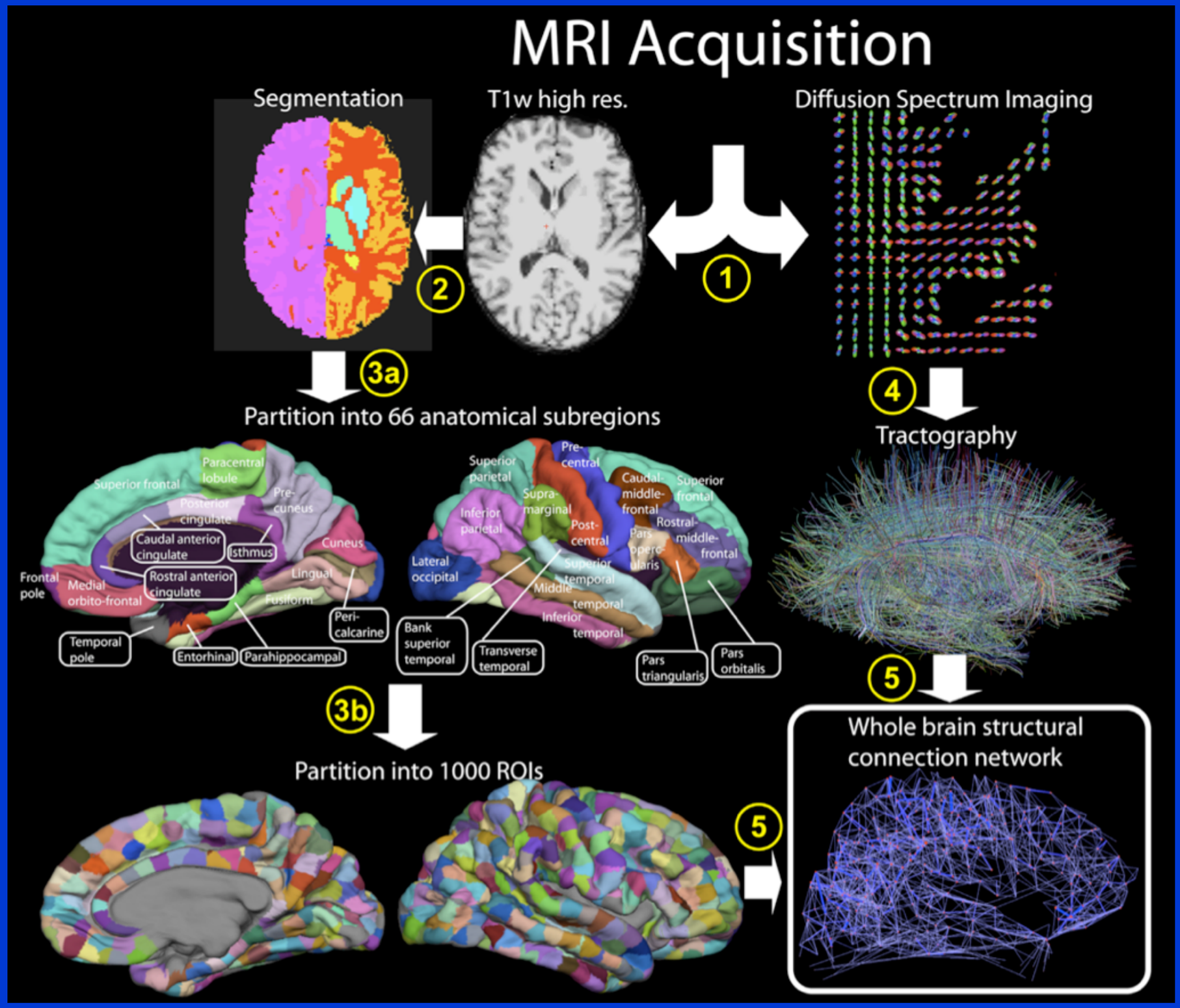




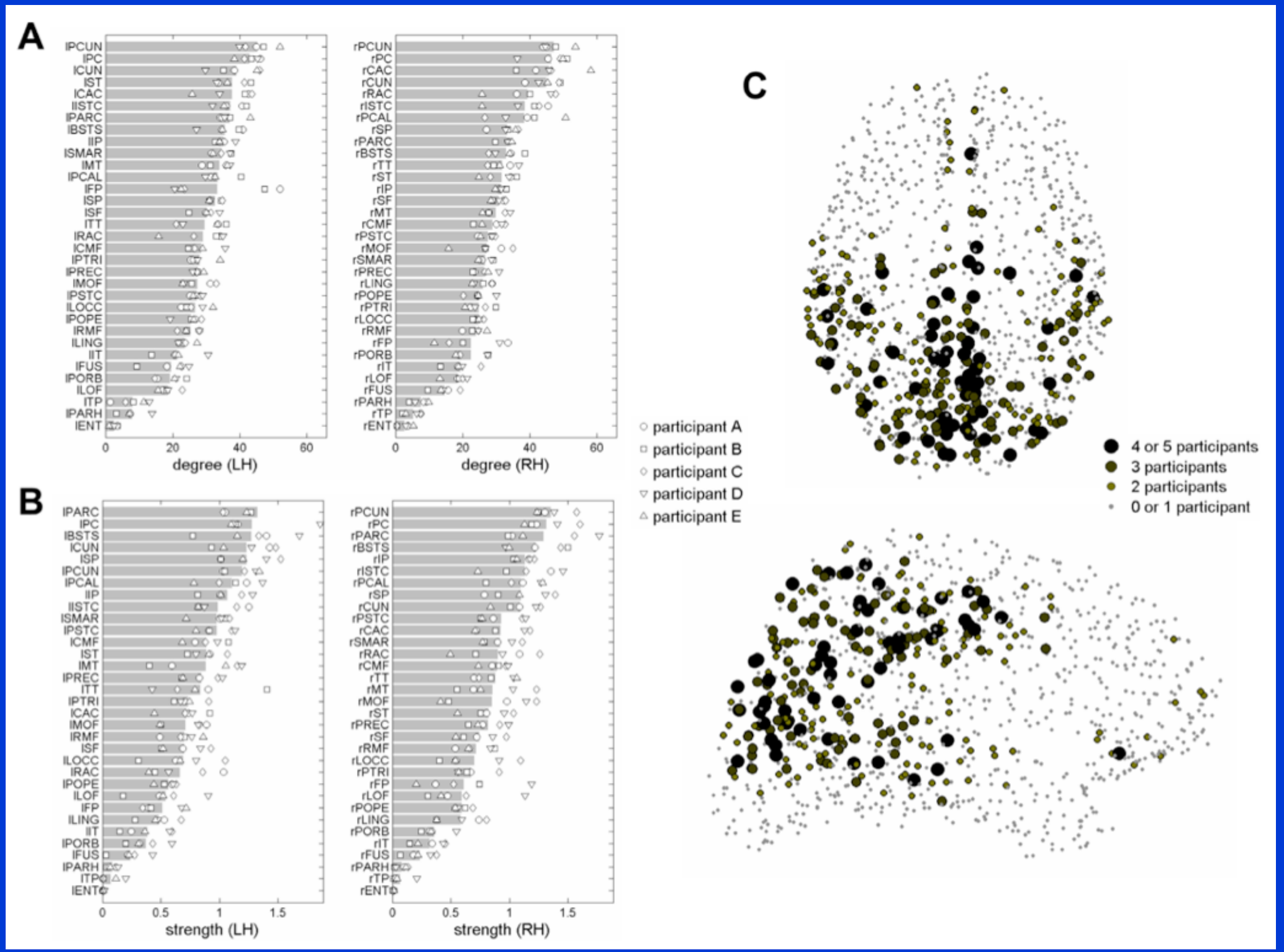


Felleman & Van Essen, Cerebral Cortex, 1991

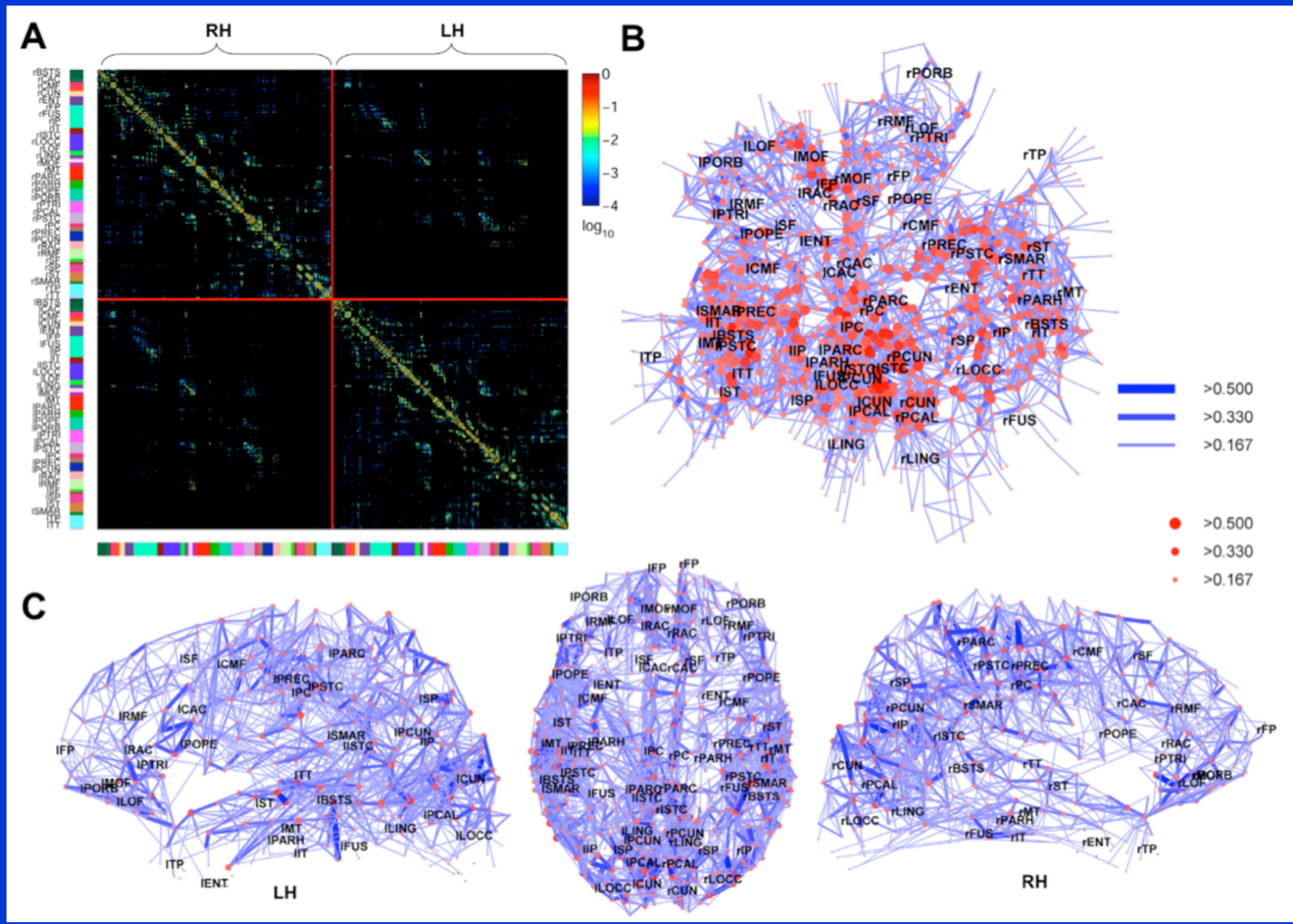
The Brain as a Network: (3) How Can We Get the Relevant Data in Humans?



The Brain as a Network: (4) Degree Distributions and Strength of Connections



The Brain as a Network: (4) Regional Connectivity Maps



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