How Computers can Help Reverse Engineer the Brain

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Who am I?

- Nik Dutt
  - Grew up in India & Japan; in USA since 1981
  - PhD in CS from Illinois in 1989
  - UCI faculty since 1989
  - Currently Chancellor's Professor and Vice-Chair
- Research Interests
  - Embedded Computer Systems: software and hardware
  - Computer-Aided Design, Computer Architecture, Compilers
  - Brain-inspired Computing
- Teaching
  - Ugrad: mainly digital design, embedded systems, architecture
  - Grad: variety of courses on advanced research topics

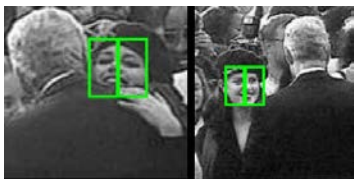
Dutt Laboratory: Who are we?

Team

- Graduate Students
  - Luis "Danny" Bathen, Arup Chakraborty, Kazuyuki Tanimura, Jun Yong Shin, Abbas Banaiyan, Codrut Stancu, Santanu Sarma, Hossein Tajikh, Satyajit Das
- Visiting Faculty
  - Prof. Gu-Min Jeong (Kookmin University, Korea)
  - Prof. Sung-Soo Lim (Kookmin University, Korea)
- Visiting Researchers
  - Dr. Yuko Hara-Azumi (Ritsumeikan University, Japan)
  - Juan Gonzalez (Monterrey Tec, Mexico)

Vision: What Machines Can't Do

- Note variations in
  - scale
  - face orientation
  - lighting
  - scene complexity, etc



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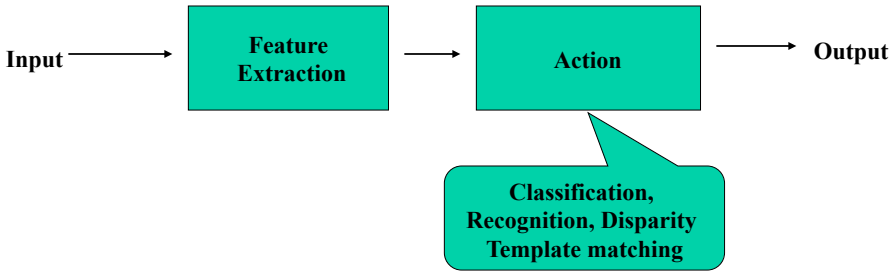
WMCD: Other Examples

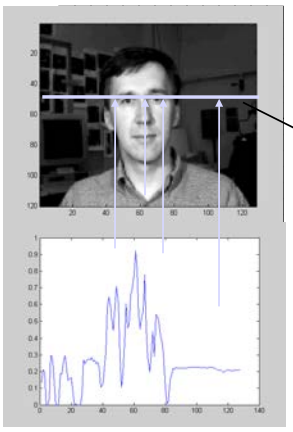
- Effective speech recognition
- Effective motor and navigation
- Planning
- Depth, color, texture perception
- Adaptation to complex environment
- Knowledge, Learning, imagination etc.
- .....

Vision: What Machines Can Do

Examples: Pattern and Machine Intelligence (PAMI) research community – basic computer vision



E.g., Face Classification



Face Locator

Feature Extraction

Classifier

Classification Decision

Source: Prof. Smyth CS175 (UCI)

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Vision Problem: The Chasm

- Machine vision (classical AI)
  - specific, well constrained problems (closed domain tasks)
  - E.g. optical character recognition or fingerprint recognition.
  - Fails in unconstrained, diverse vision problems with cluttering of view
- Biological vision (the brain)
  - Evolved to process visual data to extract just enough information to perform the reasoning for everyday tasks
  - Visual information is combined with higher level knowledge and other sensory modalities that constrain the reasoning in the solution space and finally makes vision possible.

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Outline

- The Brain: What is it?
- Reverse Engineering the Brain
- How can Computers Help?

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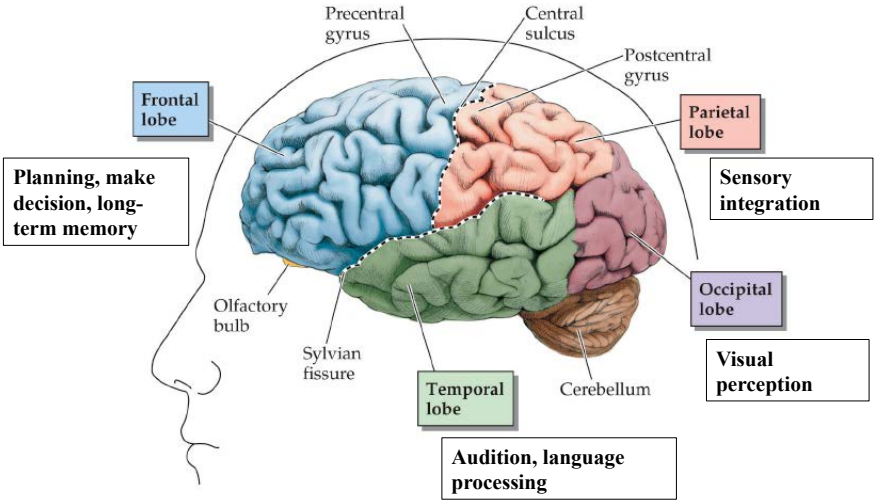
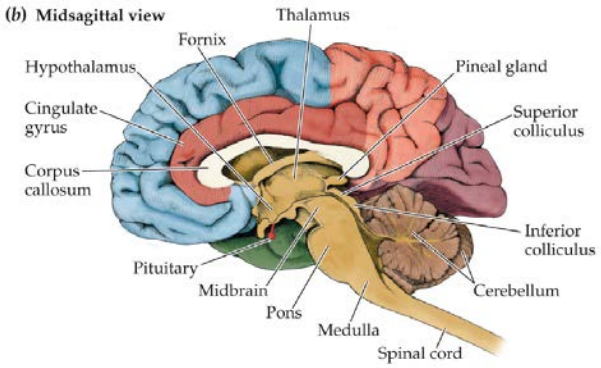
The Brain: macroscopic structures



The Human Brain: NeoCortex

NeoCortex: The "new" brain wraps around the "old" brain

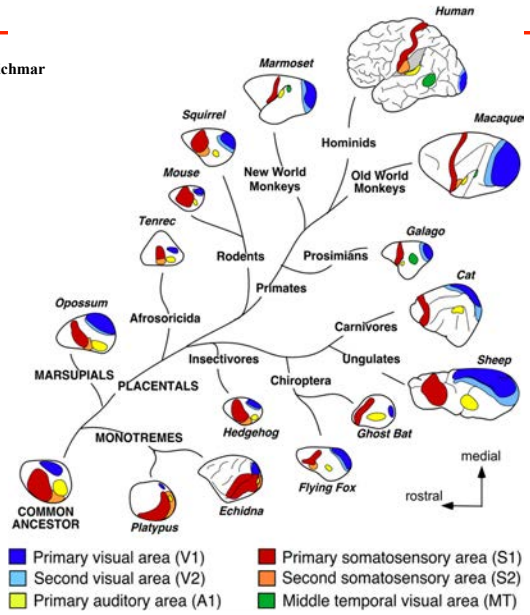
-- Distinguishes humans from other mammals



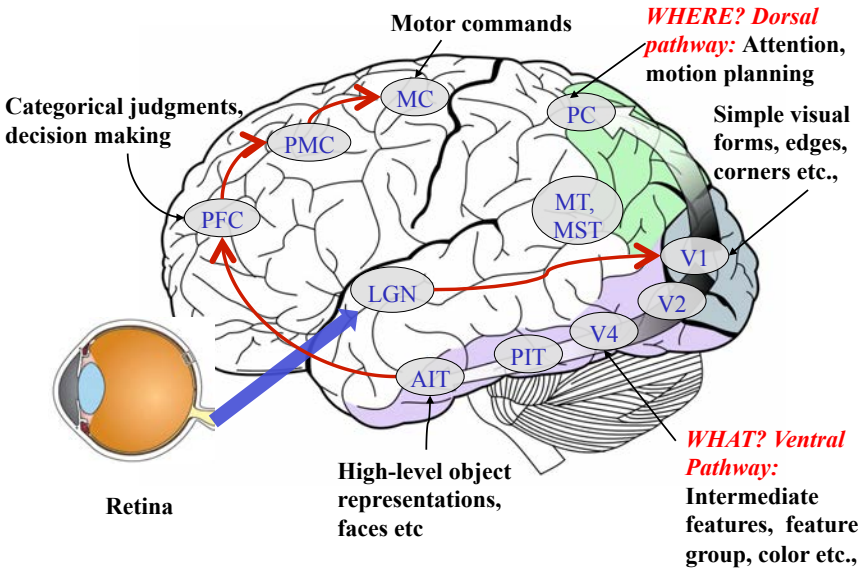
Biological Psychology 5e, Figure 2.12 (Part 2)

Common Plan of Organization in Mammals

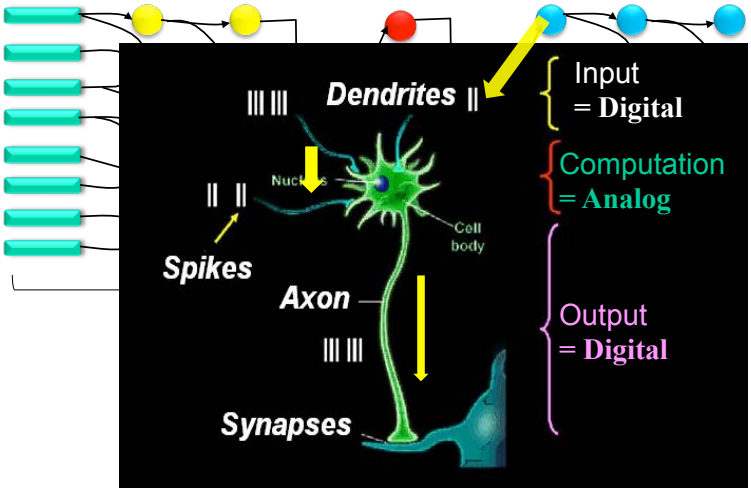
Courtesy: Prof. Jeff Krichmar



Visual Processing



Visual Pathway (simplified circuit model)



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Outline

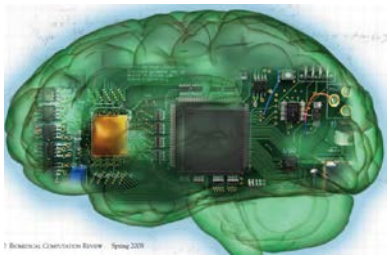
- The Brain: What is it?
- **Reverse Engineering the Brain**
- How can Computers Help?

Reverse Engineering the Brain

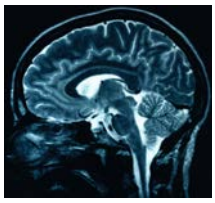
NAE GRAND CHALLENGE

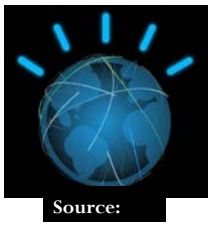
http://www.engineeringchallenges.org/cms/8996.aspx
http://www.engineeringchallenges.org/cms/8996/9109.aspx

"Understanding brain's methods will enable engineers to simulate its activities, leading to deeper insights about how and why the brain works and fails"



Brain vs. Watson !





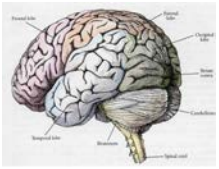
Source:

Speed:	10 Peta FLOPS	80 Tera FLOPS
Power:	20 Watts	200 Kilo Watts
Efficiency:	$500x10^6$ Mega FLOPS/Watt	400 Mega FLOPS/Watt

Brain is $1.25x10^6$ X more efficient

The Brain vs a Supercomputer

- Brain (human)
  - 1 KHz (synaptic rate)
  - 100 Billion neurons
  - **~ 20 Watts for 10 PF**
  - 1-2m/s velocity
  - **Inaccurate and slow**
- Road-runner
  - 6,912 AMDx2
  - **12,960 IBM CELL**
  - 1PF sustained
  - **3.9 MW Power**
  - 107 TB memory



The Brain: plastic connections; distributed, asynchronous, analog, non-linear; dense interconnections between regions: small-world networks

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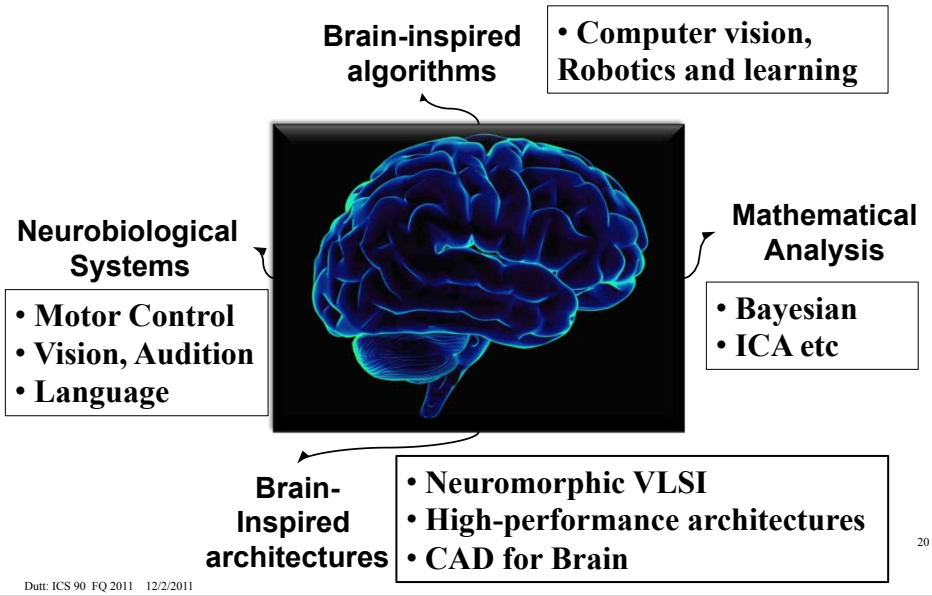
Brain-Based Research



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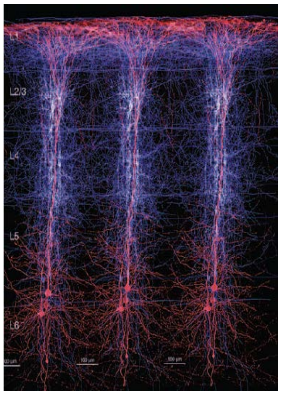
Brain Architecture

- massive parallelism (10^{11} neurons)
- massive connectivity (10^{15} synapses)
- excellent power-efficiency
  - ~ 20 W for 10^{16} flops
- low-performance components (~ 100 Hz)
- low-speed communication (~ meters/sec)
- low-precision synaptic connections
- probabilistic responses and fault-tolerant
- autonomous learning



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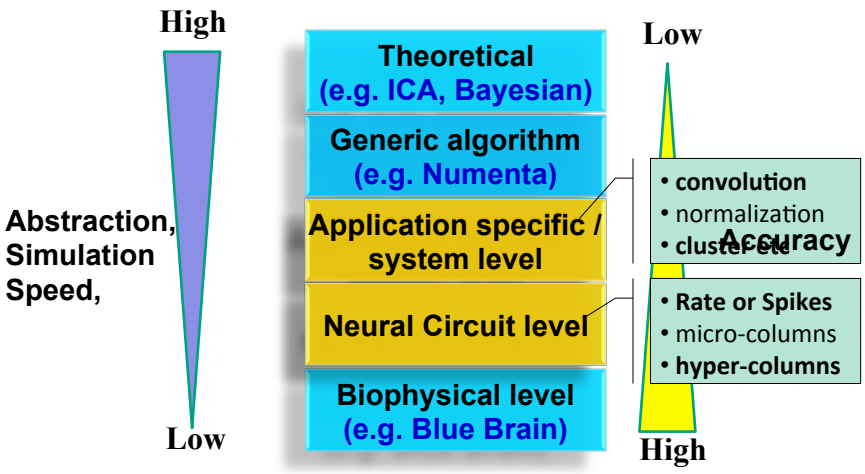
Hierarchy of Brain Models



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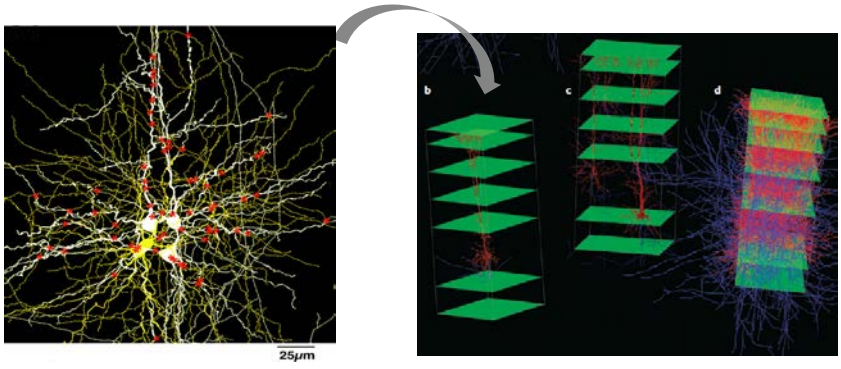
Biophysical / Cellular model

Example: EPFL Blue Brain Project: *http://bluebrain.epfl.ch/*



Precise 3D *Location* of all synapses, channels, dendritic branches and various types of neurons

Build, Simulate and Visualize a Neocortical Column using IBM BLUE GENE

Scale: cortical column with ~10,000 neurons

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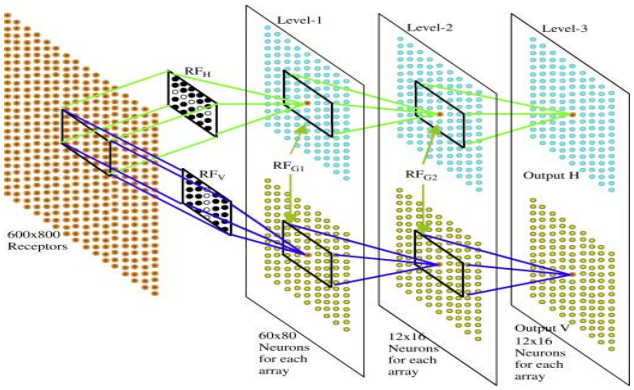
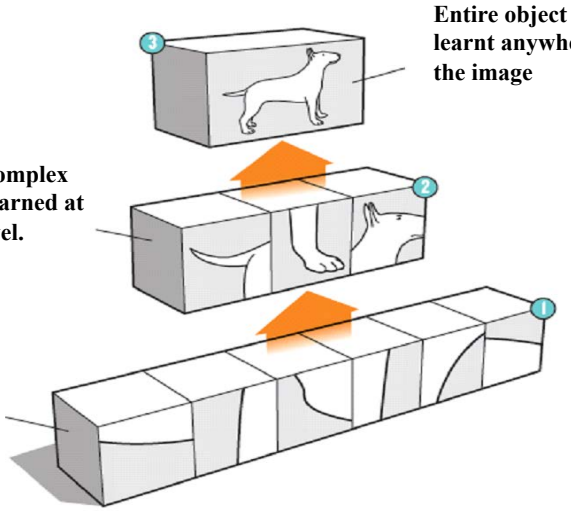
Neuron circuit model



- Commonly used model for neuroscience experiments
  - Detailed models of neurons, connectivity and synapses
  - Coding: Firing rate-based or temporal/spike-based coding
  - Example simulators: IBM cortical simulator, UCI GPU-SNN,…

Hierarchical Model for Object Recognition



Entire object is learnt anywhere in the image

More complex parts learned at next level.

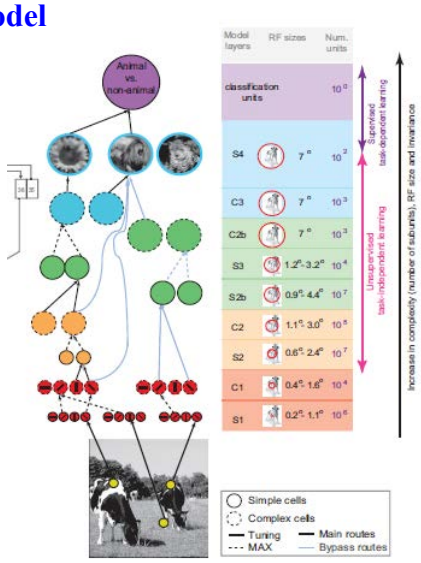
• Lower level learns simple contours. Re-used to learn many objects

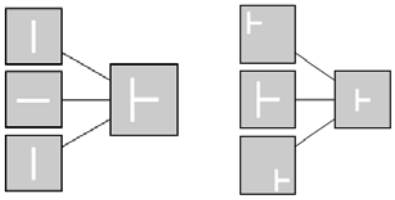
[Hawkins/Numenta IEEE Spectrum, 2007]

Another Hierarchical Vision Model

MIT H-Max Model

- Hierarchy of simple and complex unit
- Simple unit or 'AND'
  - Template matching
- Complex unit or 'OR'
  - Invariance or max-like





Simple Unit **Complex unit**

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Neuromorphic Engineering

- Building Hardware Based on the Brain's Structure and Dynamics

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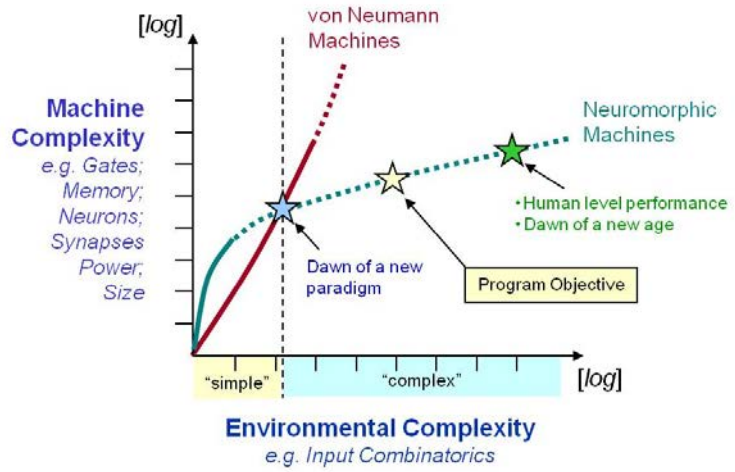

DARPA SyNAPSE Project - HRL Team

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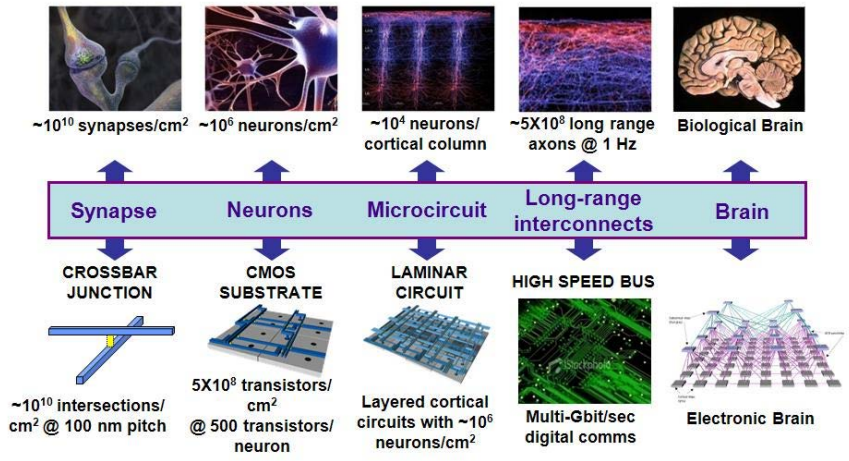
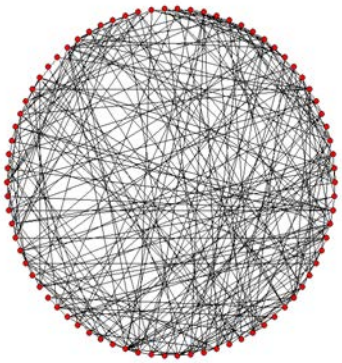


What are brain networks?

- What is a network?
  - ➔ Nodes and connections are two basic elements of a network.

A network (graph)



- What are the nodes and connections of brain networks and how do we define them?
- How many types of brain networks are there according to scale, physiology, and anatomy?

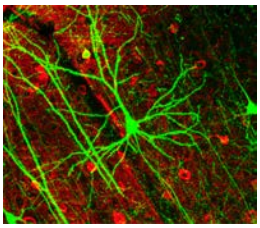
Scales and levels of brain networks

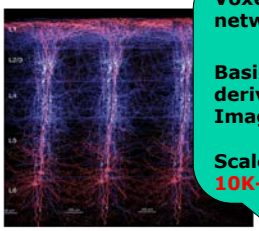
- Basic structure of brain networks (node and connection) can be defined at different scales.

Microscale: neurons and their synaptic connections (about 10^{10} neurons in the cortex).

Mesoscale: connections within and between minicolumns (about 2×10^{8} minicolumn in the cortex).

Macroscale: anatomically distinct brain regions and inter-regional pathways (about 100 regions in the cortex).





Voxel based Brain network Analysis

Basic elements can be derived from Medical Imaging Techniques

Scale: 10K-100K

Neurons | Columns | Regions

Sporns et al (2005) PLoS Comput Biol

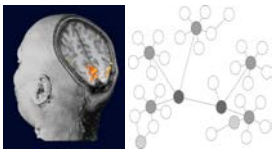
Relationship to Physiology and Anatomy

- Basic types of brain networks can be described in terms of physiology and anatomy.
  - **Functional brain networks:**
    - **Functional connectivity:** temporal correlation between spatially remote neurophysiological events
    - **Effective connectivity:** causal effects of one neural system over another
  - **Structural brain networks:**
    - **Structural connectivity:** physical or structural (synaptic) connections linking neuronal units
    - **Morphometric connectivity:** statistical interdependencies of morphological features between different brain regions such as the cortical thickness, gray matter volumes, density, areas and complexity

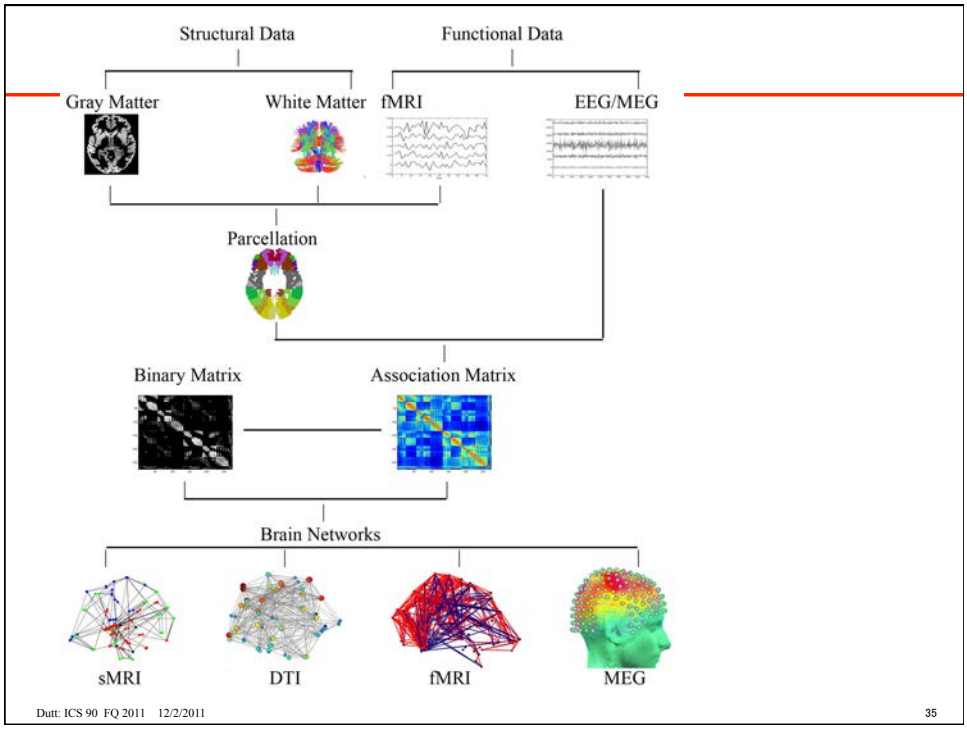
Brain Network Analysis (BNA)

Non-invasive technique: Medical Imaging

- Imaging techniques + Graph theory
  - **functional MRI**, diffusion tensor MRI, structural MRI, …



- Reveal the properties of the brain
  - Small world, Scale free [Heuvel 2008]
  - Efficiency
  - Modular structure [Valencia 2009]
  - …
- Understand the mechanism of brain diseases
  - Alzheimer's disease [He 2008; Supekar 2008; Lo 2010]
  - Schizophrenia [Bassett 2008; Zalskey 2010; Liu 2008]
  - Depression [Zhang 2011]
  - …



Human Connectome Project

Human Genome Project (HGP (1990-2003)

- Figure out brain's structural & functional connectivity
  - NIH Human Connectome Project (2010-2015)

http://humanconnectome.org/

Human Connectome: Mapping structural and functional connectivity in the human brain

5 years, $30 million, 2 consortiums, 4+ universities/hospitals, for the basic analysis method and acquiring data

Recap: What Did We Cover Today?

- Challenges in Reverse-Engineering the Brain
  - Visual cognition as an example
- Brain-derived models and parallels to computing
- Opportunities for computer science research

The Brain: Some Closing Thoughts….

- "The human brain starts working the moment you are born and never stops until you stand up to speak in public."
  - George Jessel

- "Knowledge fills a large brain; it merely inflates a small one."
  - Sydney Harris
- "Brain: An apparatus with which we think we think."
  - Ambrose Bierce, The Devil's Dictionary

Acknowledgements

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  - Dr. Jayram Moorkanikara, Computer Science/UCI
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