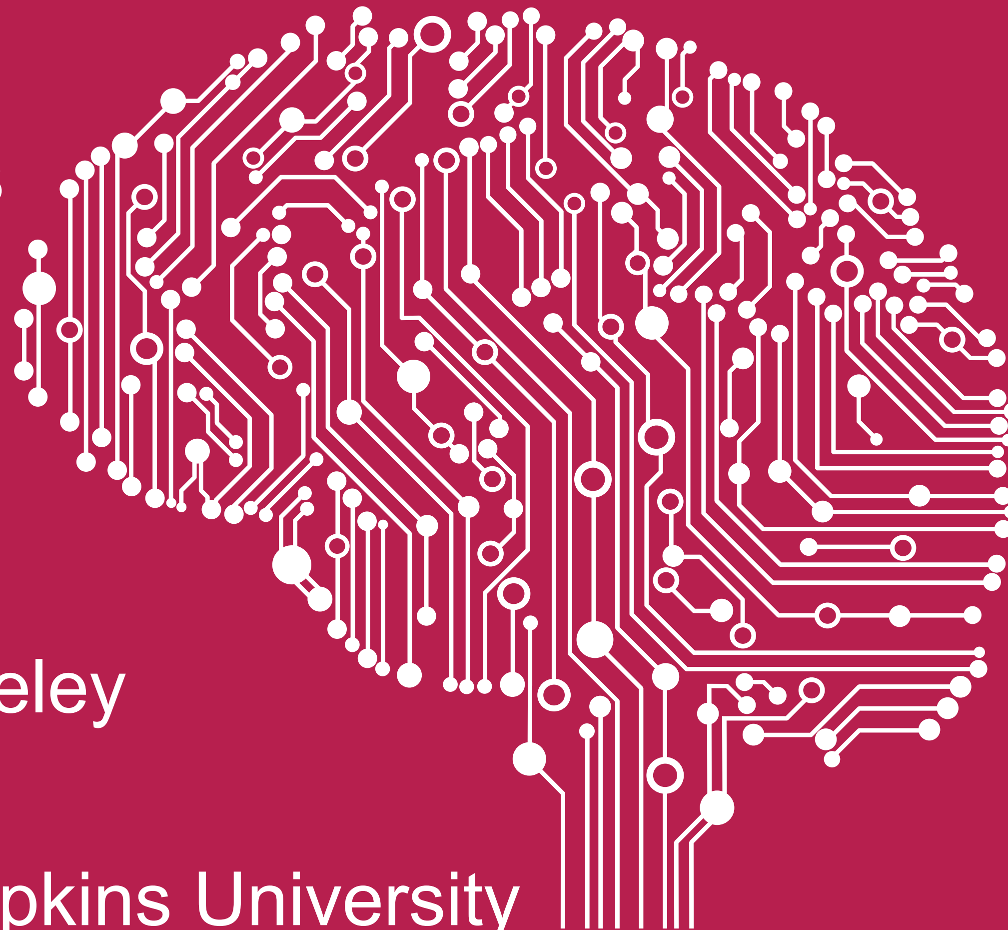
Research Interfaces between Brain Science and Computer Science



Jack Gallant, UC Berkeley
Polina Golland, MIT
Greg Hager, Johns Hopkins University

http://cra.org/ccc/events/brain-workshop/

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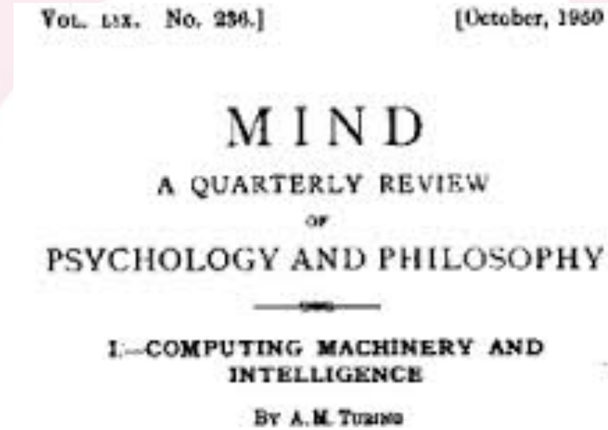
THE HISTORY OF COMPUTING AND BRAIN ARE INTERTWINED

- Turing: *Computing Machinery and Intelligence* (1950)
  - What is intelligence? Are there fundamental reasons machines cannot be intelligent?



Vol. LIX. No. 236.] [October, 1950

MIND

A QUARTERLY REVIEW

OF

PSYCHOLOGY AND PHILOSOPHY

I.—COMPUTING MACHINERY AND INTELLIGENCE

By A. M. Turing

- Von Neumann: *The Computer and the Brain* (1958)
  - Is the brain a machine like a computer?

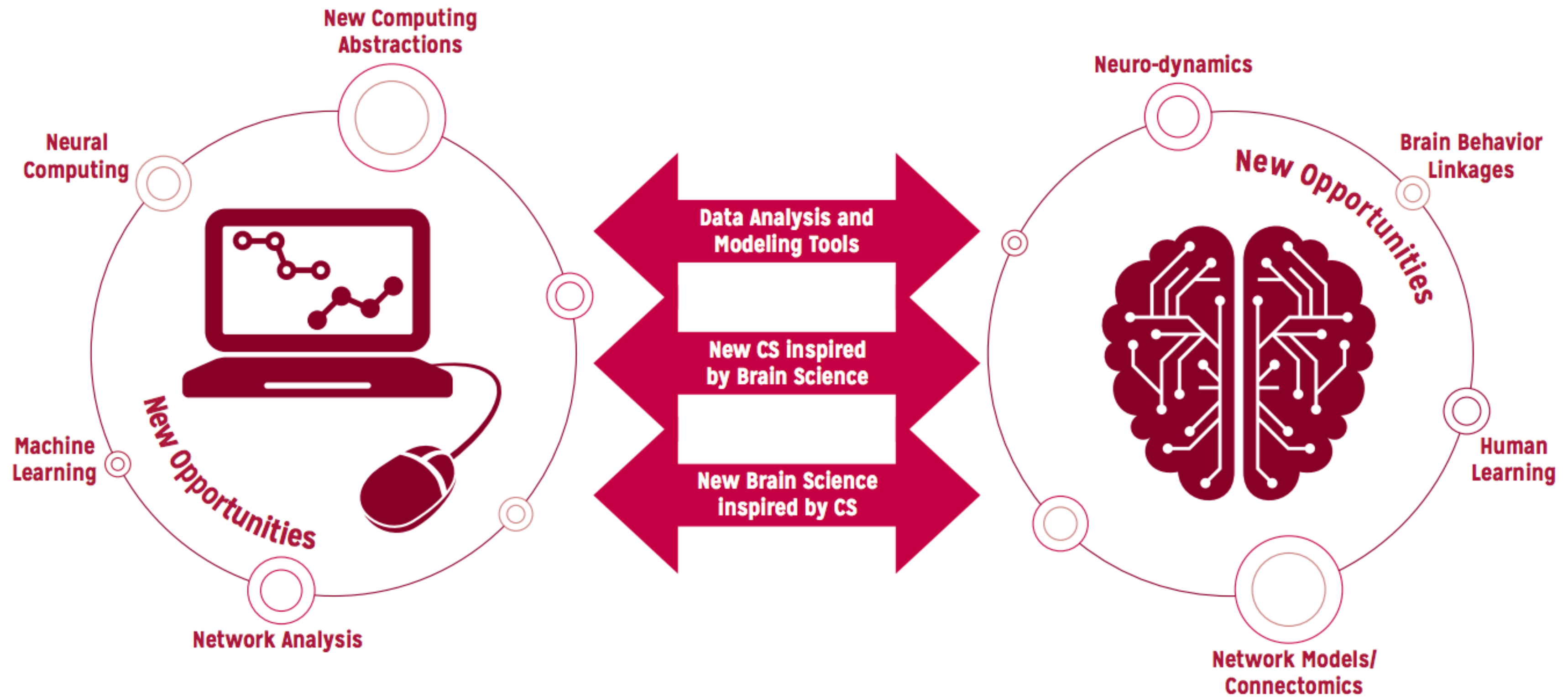
- Herb Simon: (1957)
  - Most theories in psychology will take the form of computer programs.

TIMES HAVE CHANGED

Exponential advances in of computing and concomitant advances in approaches to brain sciences have ignited new opportunities:

- Data related to brain research has exploded in diversity and scale, providing unprecedented resolution of both anatomy and function across a growing population of individuals
- Access to enormous computational power coupled with computational data science tools has been revolutionized by the growth of cloud-based computing platforms.
- The success of new models for machine learning inspired by neural architectures is reigniting directions of inquiry on biomimetic algorithms.
- New methods for acquiring and processing behavior data “at scale” are emerging from the mobile device revolution, providing new possibilities for brain scientists to connect behavior to function.

REBOOT INTERACTION BETWEEN CS AND BRAIN SCIENCE

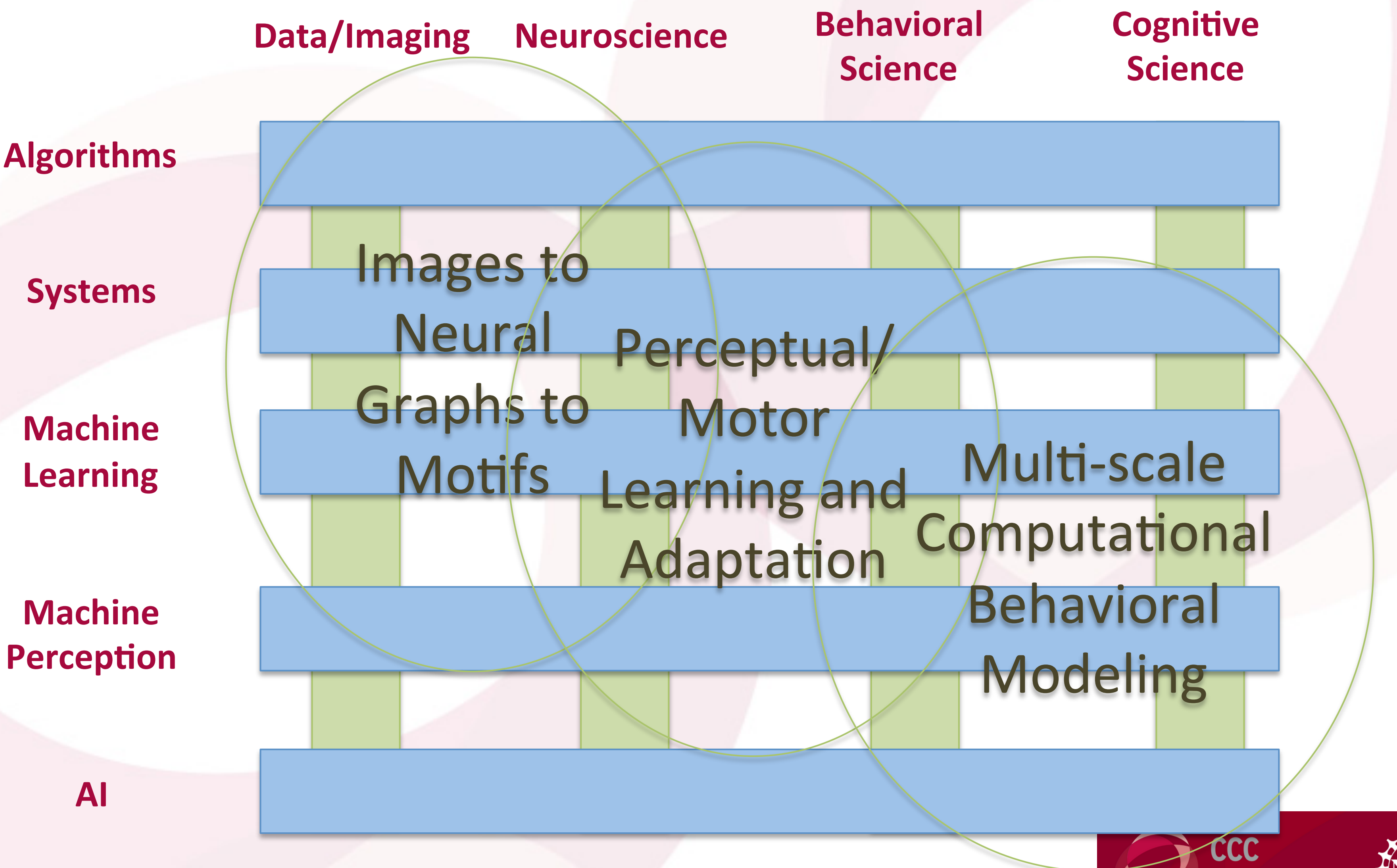


Beyond "one-way" thinking

CCC-NSF BRAIN WORKSHOP: PARTICIPANTS

- 72 Total Attendees
- 20 from Government Agencies
  - NSF, IARPA, DARPA, NIH
- 2 Foreign Attendees
  - Italy, UK (Human Brain Project)
- 3 Foundation Attendees
  - Kavli Foundation
- 4 Industrial Attendees
  - Neurospin, IBM, Facebook

CCC-NSF BRAIN WORKSHOP AREAS



PLENARIES

- Aude Oliva, MIT: *Time, Space and Computation: Converging Human Neuroscience and Computer Science*
- Jack Gallant, UC Berkeley: *A Big Data Approach to Functional Characterization of the Mammalian Brain*
- Leslie Valiant, Harvard: *Can Models of Computation in Neuroscience be Experimentally Validated?*
- Terrence Sejnowski, Salk Institute: *Theory, Computation, Modeling and Statistics: Connecting the Dots from the BRAIN Initiative*

PANELS

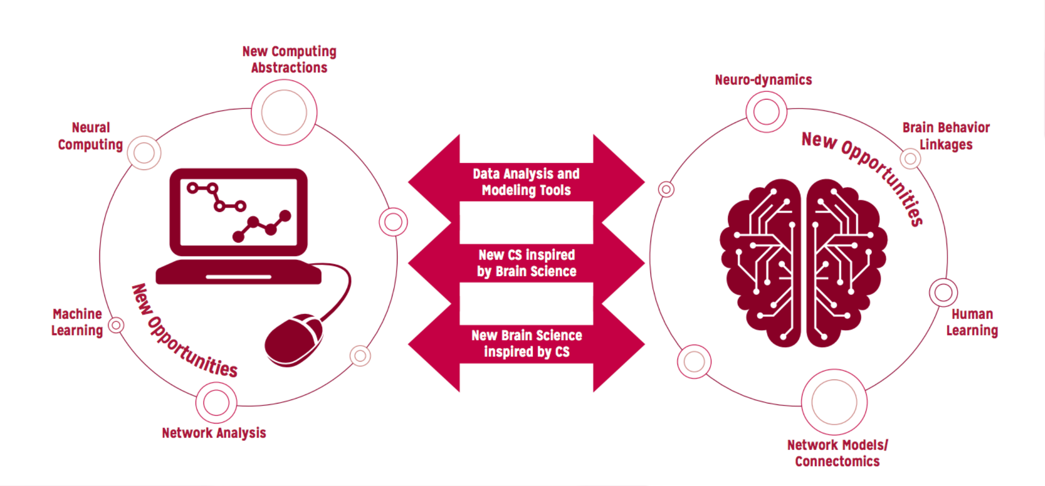
- **Brain Mapping:**
  - Jeff Lichtman Charless Fowlkes, Ragini Verma, James Haxby, **Polina Golland**
- **Brain / Mind / Body**:
  - Matt Botvinick, Naomi Hannah Feldman, Konrad Koerding, Raj Rao, **Stefan Schaal**
- **Computing and the Brain**
  - Shafi Goldwasser, Yann Lecun, Pietro Perona, Leslie Valiant, Bruno Olshausen, **Sanjeev Arora**
- **Creating Open-Science Platforms for Heterogeneous Brain Data**
  - Jeremy Freeman, Greg Farber, Joshua Vogelstein, Sean Hill, **Miyoung Chun**

BREAKOUT THEMES

- **Brain Architecture** (Pfister)
  - Barriers to mapping the architecture of the brain; how can they be overcome?
  - What are/ what scale of data suffices to discover of "neural motifs."”
- **Computing and Neuroscience** (Arora)
  - What advances in computing are needed to support empirical neuroscience?
  - Can study of algorithms/systems help cast light on the brain’s function/structure?
- **Brain and Behavior** (Schaal)
  - Creating big data for behavior / movement / cognitive sciences
  - What computational tools would this require/enable?
- **Multi-scale Multi-modal modeling** (Duncan and Whitaker)
  - How can we bridge the gap from what the brain is and what it does?
  - Are there ways to integrate neuroscience, cognitive, and behavioral science through the development of common computational tools and analysis methods?
- **Studying the brain to transform computing** (Olshausen and LeCun)
  - Natural and machine learning
  - Natural and machine perception

REPORT THEMES

1. Modeling
2. Connecting Brain, Mind, and Body
3. Data Challenges
4. Computing Opportunities



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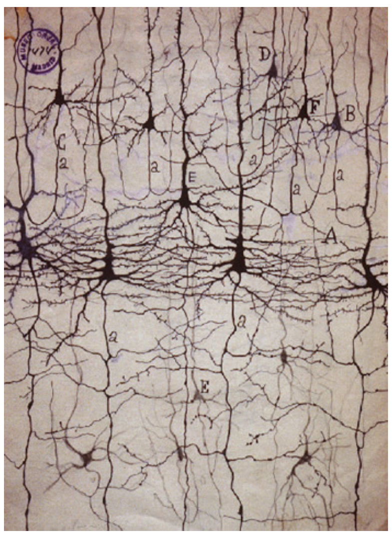
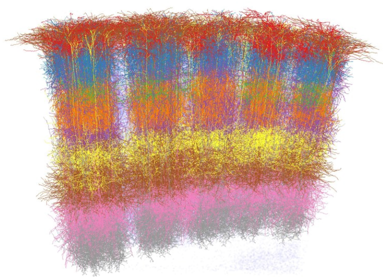
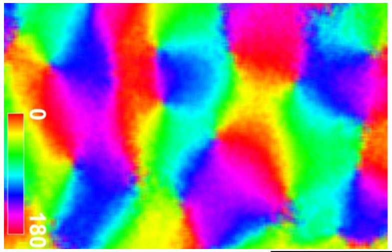
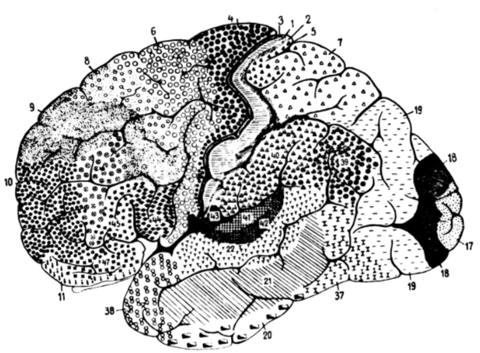
MODELING

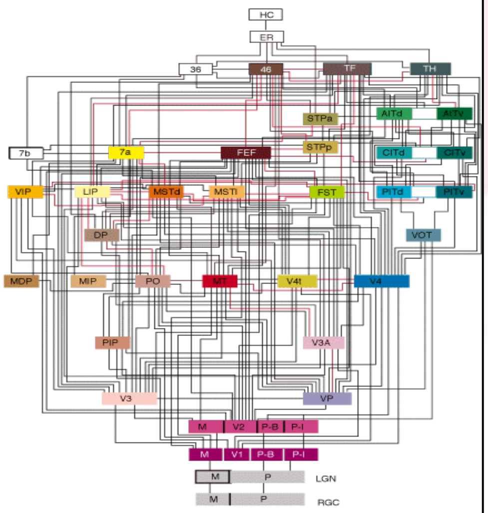
- The brain is a biological computer that functions quite differently from a conventional computer.
- Our understanding of the brain is limited both by measurement and by computation.









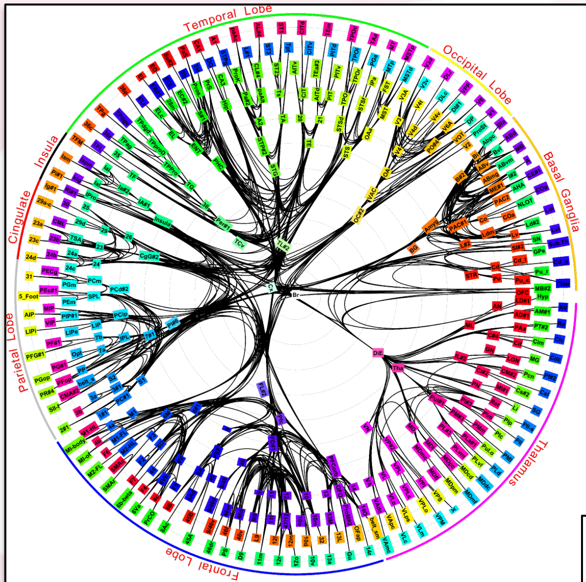


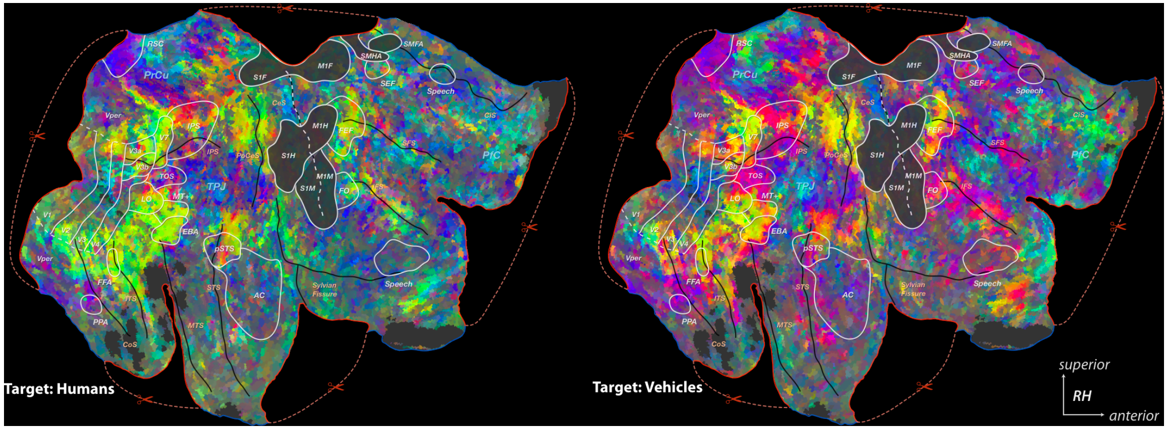
The human brain:
18 billion cortical neurons
1-10 thousand synapses/neuron
5 million cortical columns ?
500 areas and nuclei?
12000 inter-areal connections?

Cajal, 1888; Oberlander et al, 2012
Oki, Chung, Kara et al., 2006
Felleman & Van Essen, 1992
Modha & Singh, 2010

Basic computer science relevant to neuroscience

- Neural modeling uses tools developed originally for different purposes in computer science and engineering.
- Further development in a variety of mathematical areas will be critical for advancing neural modeling.





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18 billion cortical neurons
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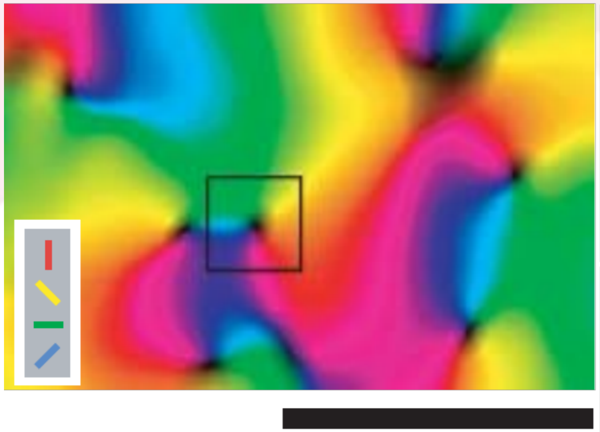
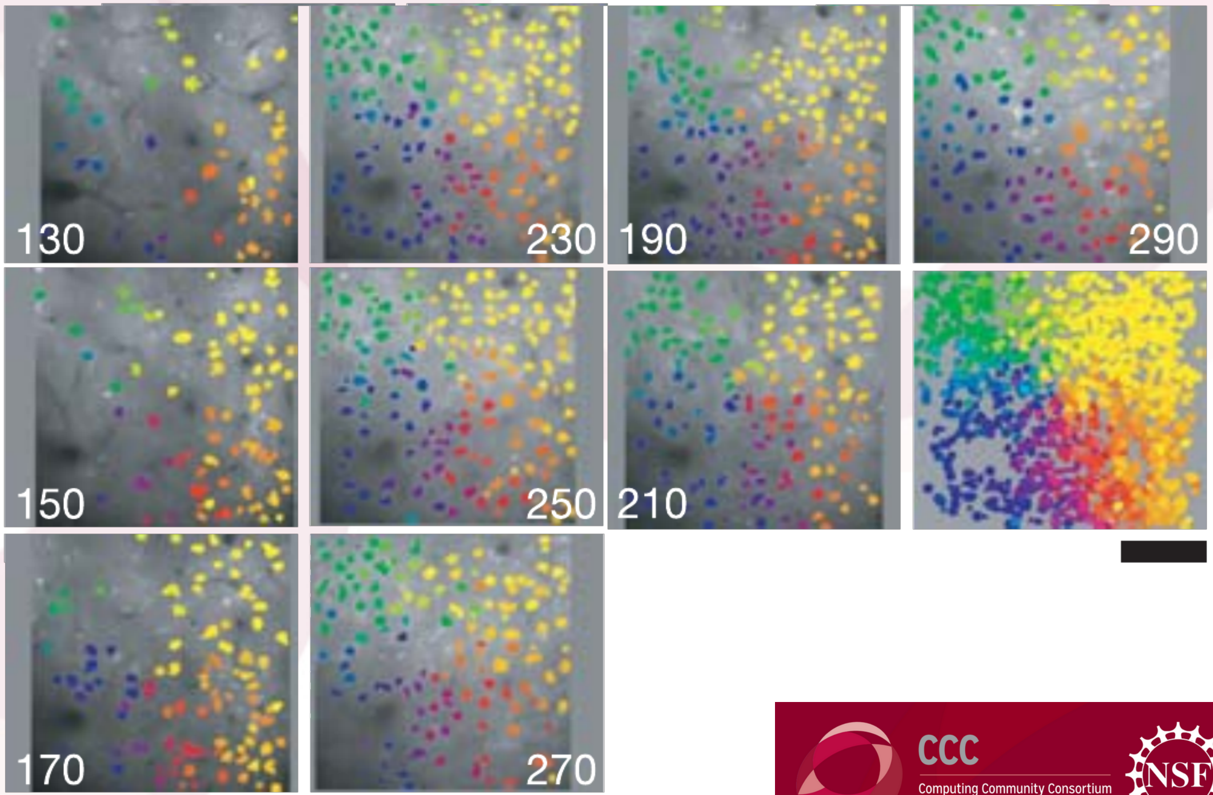
Cukur & Gallant, 2013
Modha & Singh, 2010

Data analysis/modeling at multiple scales and modalities

- Future brain data will be larger, from more measurement modalities and across more spatial and temporal scales.
- We need new computational tools to deal with these multi-scale data and to facilitate data fusion.

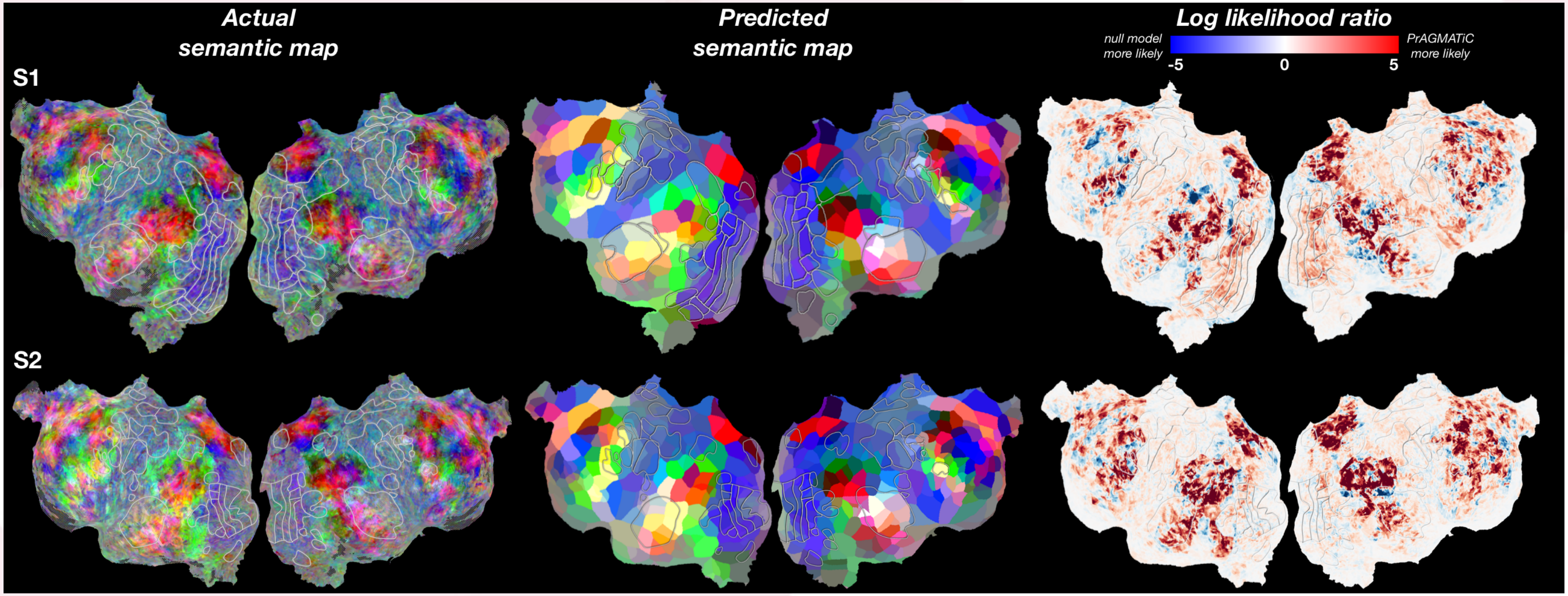




Ohki, Chung, Kara, Hubner, Bonhoeffer & Reid, *Nature*, 2006

Data analysis/modeling at group and individual levels

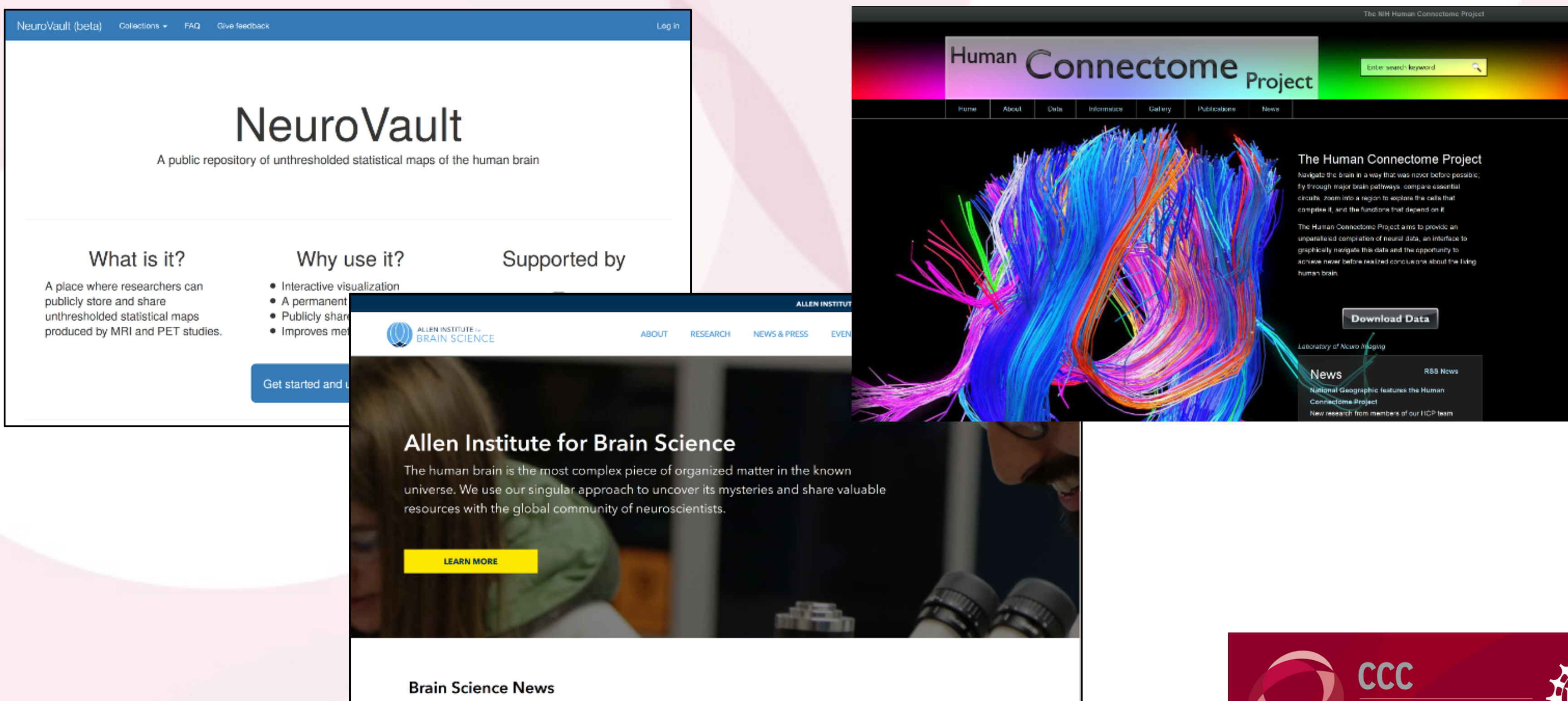
- Most current neuroscience work focuses on the group level, but individual differences are becoming important.
- We need computational tools for modeling individual differences and their relationships to the group.



Huth, de Heer, Griffiths, Theunissen & Gallant, *in press*

Data and model sharing and processing

- As neuroscience data grow the needs to share, archive, curate, access, process and model the data will grow.
- We need new methods for efficiently dealing with large, shared data and for automatically processing those data.



BRAIN, MIND, BODY

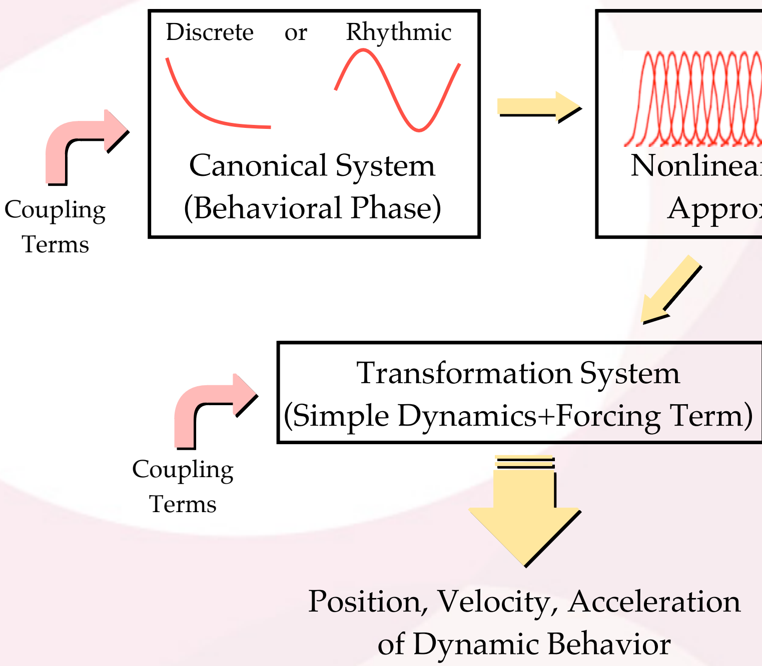
- Observation: Over half the brain is devoted to sensing and motor activity
  - We are embedded in a complex physical world; understanding the brain is only half the answer
  - The brain has to account for (and take advantage of) the physical world
- BMB Challenges
  - Spans neuro/cognitive/behavior sciences
  - Massive diversity of data – quantity, quality, and form
  - Massive diversity in methodology
  - Multiple scales of abstraction

EXAMPLE: MOVEMENT PRIMITIVES IN HUMANS AND ROBOTS

- Foundations of human (primate) movement generation:
  - Movements can be classified into rhythmic (locomotion, scratching) and discrete (reach, grasp, touch)
  - Theories of primate movement generation in biology explain both with one mechanism
  - Computational theories based on dynamic systems theory postulate different mechanisms for generating rhythmic and discrete movement
  - Which is right?

EXAMPLE: MOVEMENT PRIMITIVES IN HUMANS AND ROBOTS

- A computational model inspired from behavioral and neuroscientific data advances the theory of movement planning, optimization, execution in humans and robots (Ijspeert et al, Neural Computation 2013)



$$\tau\ddot{y} = \alpha_z\left(\beta_z\left(g-y\right)-\dot{y}\right)+f\left(x\right)+C_z$$

$$\tau\dot{x} = -\alpha_x x + C_x$$

$$f\left(x\right)=\frac{\sum_{i=1}^{k} w_i b_i x}{\sum_{i=1}^{k} w_i} = \mathbf{b}^T \boldsymbol{\phi}\left(x\right)$$

where

$y, \dot{y}$ are the desired position and velocity of a movement

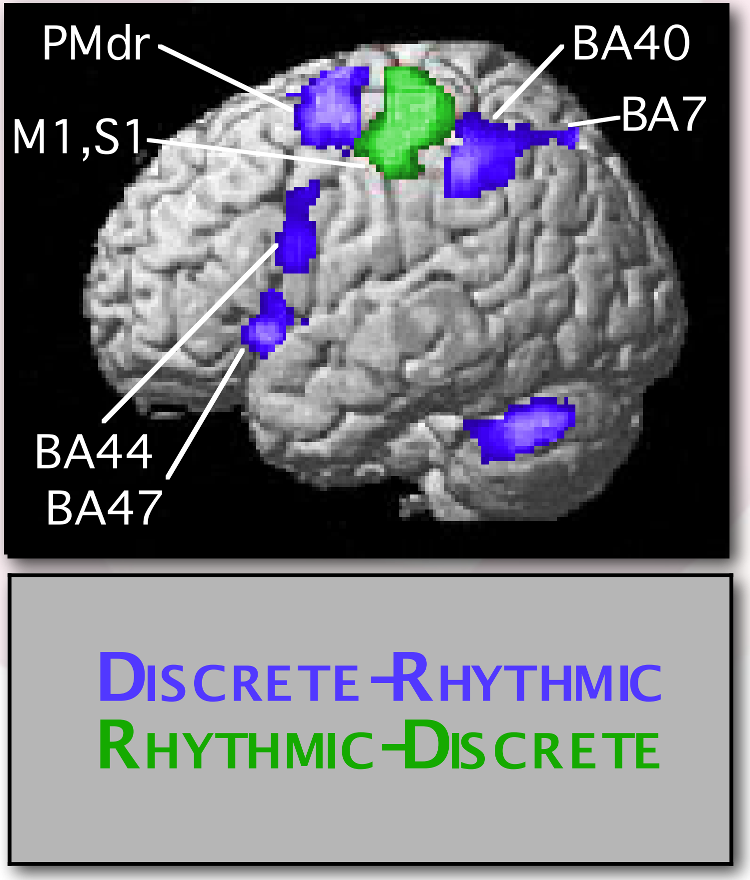
$f\left(x\right)$ is a nonlinear function approximator

g is the goal state of the movement

C_x, C_z are coupling terms

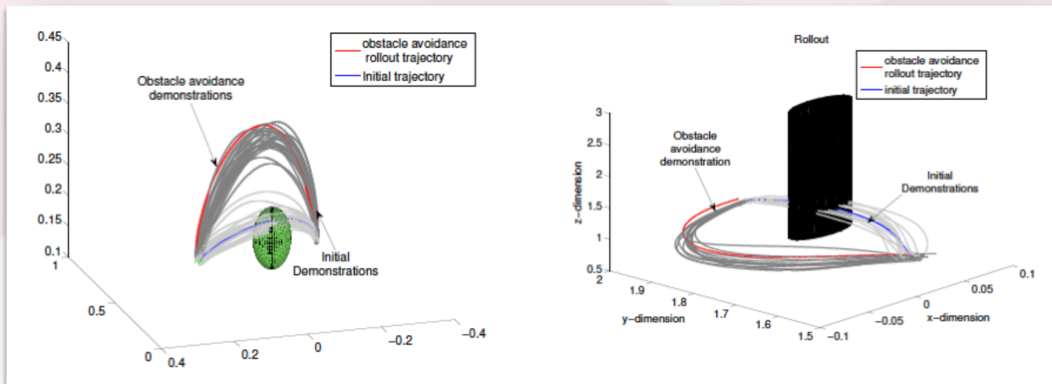
EXAMPLE: MOVEMENT PRIMITIVES IN HUMANS AND ROBOTS

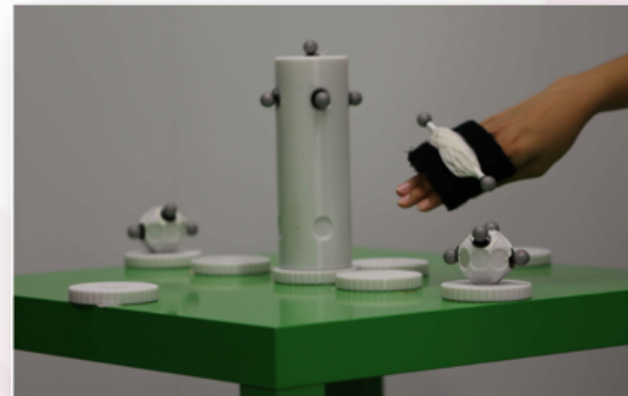
- fMRI Study of Rhythmic vs. Discrete Wrist movement:
  - Major result: the human brain employs different areas in the generation of rhythmic and discrete movement, indicating that these classes of movement should be studied and modeled separately (Schaal et al., Nature Neuroscience 2004)



EXAMPLE: MOVEMENT PRIMITIVES IN HUMANS AND ROBOTS

- The computational model has been successfully used in models of human behavior and robot motion generation.





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OTHER EXAMPLES OF BMB OPPORTUNITIES

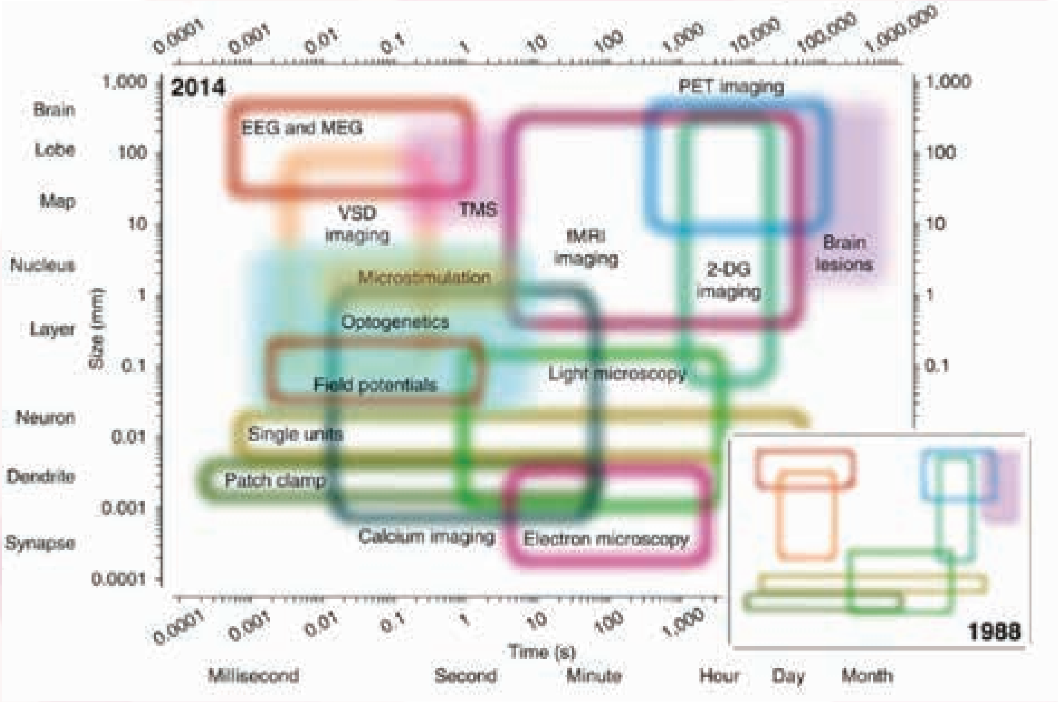
- Creating linked internal/external data sources
  - Controlled experimental
  - “Found” – e.g. Fitbit movement data in the wild
  - Simulated

- Marrying controlled experimental data with clinical data at scale
  - Narrow deep wells together with massive shallow data

- Create community-wide computational reference models that span areas of investigation

DATA

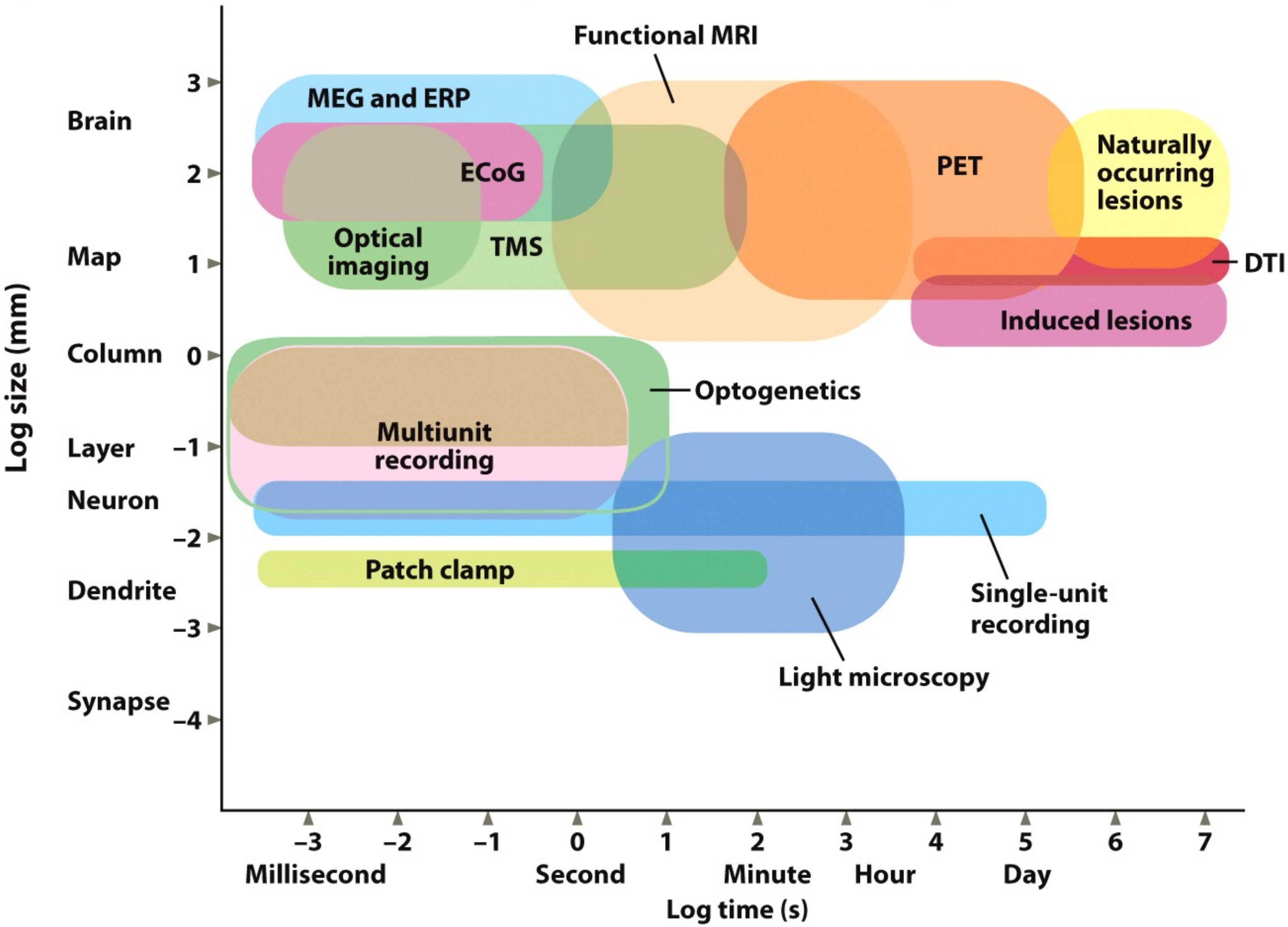
Is neuroscience the “next big data science”?



ontemporary measurements of brain structure and function from

Table 1: List of useful brain sciences data resources

URL	Utility
http://openconnecto.me	Open science data & software
http://www.incf.org/resources/research-tools	Neuroinformatics tools
http://web.stanford.edu/group/brainsinsilicon/challenge.html	Dedicated neuromimetic hardware
https://wiki.humanconnectome.org/display/PublicData/Connecting+to+Connectome+Data+via+AWS	Commercial cloud storage solution for neuroscience
http://www.birncommunity.org/resources/data/	Federal database of certain brain imaging data
http://crcns.org/data-sets	Home-grown brain data repository
http://www.loni.usc.edu/Software/Pipeline	Pipelining software for distributed computing
http://www.nature.com/sdata/	Journal dedicated to publishing datasets
http://www.humanconnectome.org/data/	Publicly shared dataset
http://fcon_1000.projects.nitrc.org/	Consortia of publicly shared datasets



Functional MRI
MEG and ERP
ECoG
Optical imaging
TMS
PET
Naturally occurring lesions
DTI
Induced lesions
Optogenetics
Multiunit recording
Patch clamp
Single-unit recording
Light microscopy
Log size (mm)
Brain
Map
Column
Layer
Neuron
Dendrite
Synapse
3
2
1
0
−1
−2
−3
−4
−3
−2
−1
0
1
2
3
4
5
6
7
Millisecond
Second
Minute
Hour
Day
Log time (s)

SOME EXAMPLES OF DATA OPPORTUNITIES

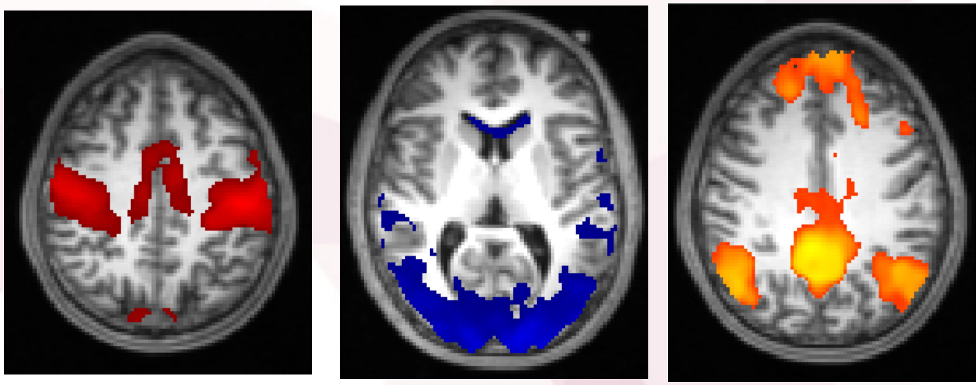
- Creating a community “brain observatory”
- Developing tools that mirror e.g. galaxy tools for genomics
- Creating models that promote anonymous federated sharing and analysis
- Developing novel methods for extracting relevant structure from noisy, incomplete observations of the brain
- Developing new computational tools for aggregating data and for building probabilistic structural and functional atlases

A CONCRETE EXAMPLE OF CS/BRAIN DATA ADVANCE

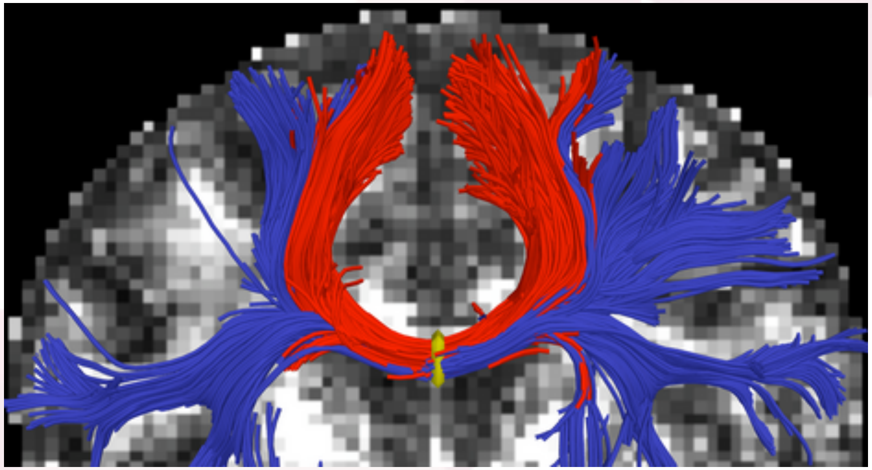
- Computational methods to analyze neuroimage data (MRI,fMRI, dMRI,M/EEG)
  – Models of observed signals informed by neuroscience
  – Analysis methods informed by geometric modeling and statistical inference
- Examples:
  – Functional organization of the visual cortex via clustering and spectral matching of fMRI and/or MEG
  – Topic modeling of brain processes from large collections of activation data
  – From diffusion to connectivity and brain parcelation

EXAMPLE: FROM PIXELS TO MODELS OF BRAIN

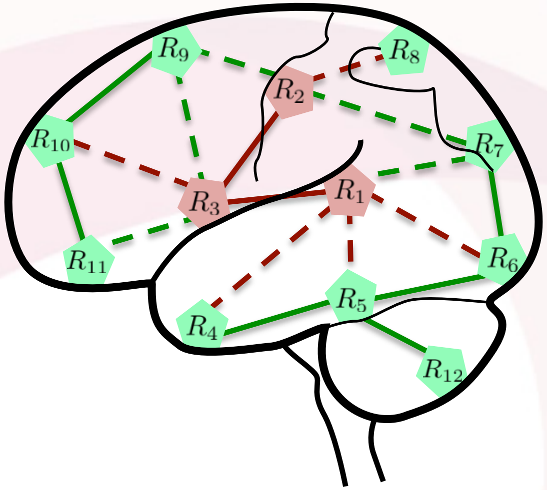
- Functional connectivity



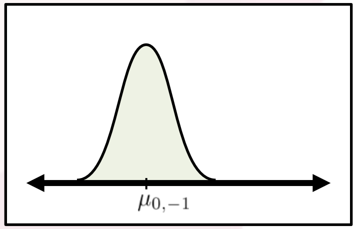
- Anatomical connectivity

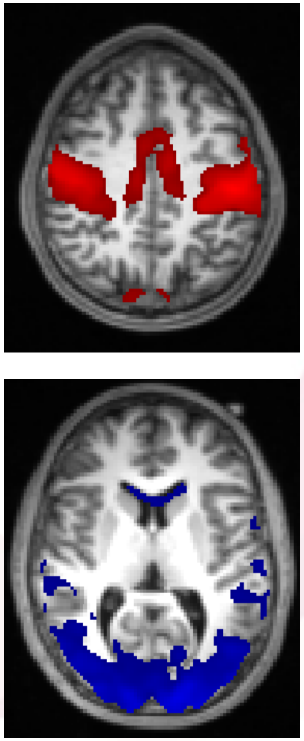


GENERATIVE MODEL: FROM NETWORKS TO DATA



$$P(B^l_{ij} | A_{ij} = 0, F_{ij} = -1; \Theta)$$

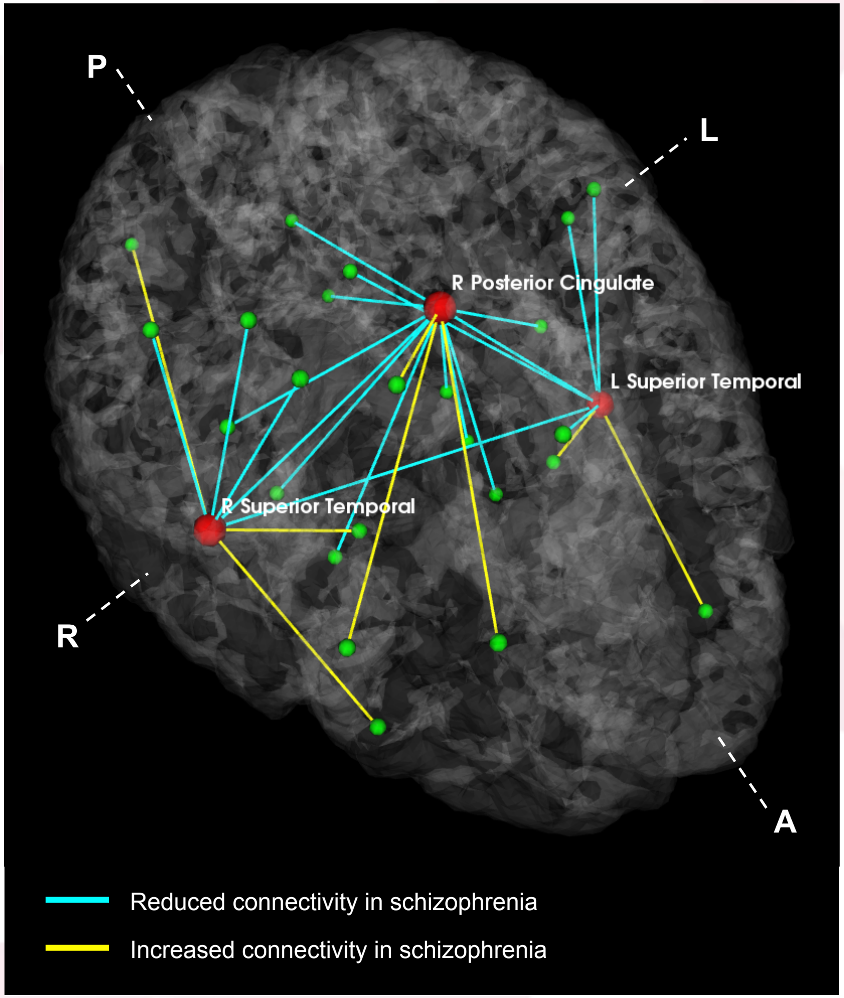




- Computational search for subset of nodes
  - statistical inference
  - optimization

Venkataraman *et al.* 2012

RESULT: PERTURBED NETWORK



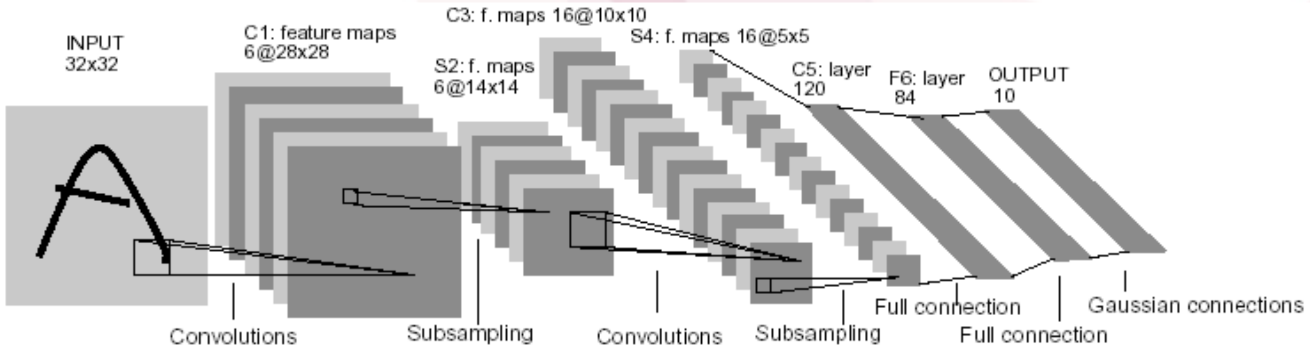
Venkataraman *et al*. 2012

CS FOR BRAIN DATA

- Data management and sharing
- Computational models of the brain
  - Based on current brain models
  - From data to insight
  - Guide further brain modeling
- Need and potential for a new type of computational scientists who are well versed in the domain knowledge

COMPUTING

- Numerous cross-cutting computational opportunities:
  - Machine learning vs. human learning
  - Machine perception vs. human perception
  - Machine language understanding vs. human
  - Machine motor control vs. human motor control

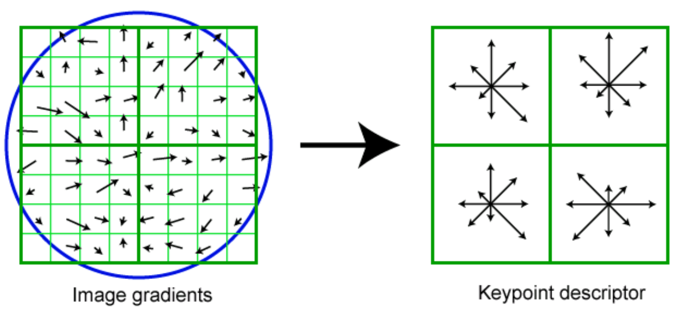


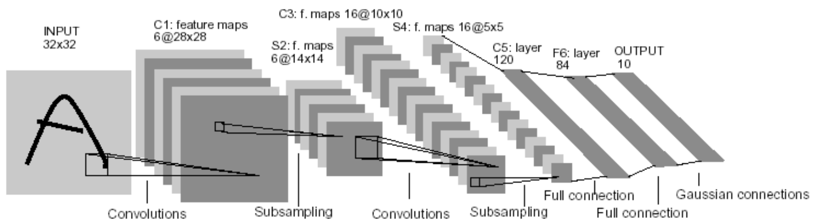
Borrowing New Ideas from Human Vision

David Lowe

Google Seattle,

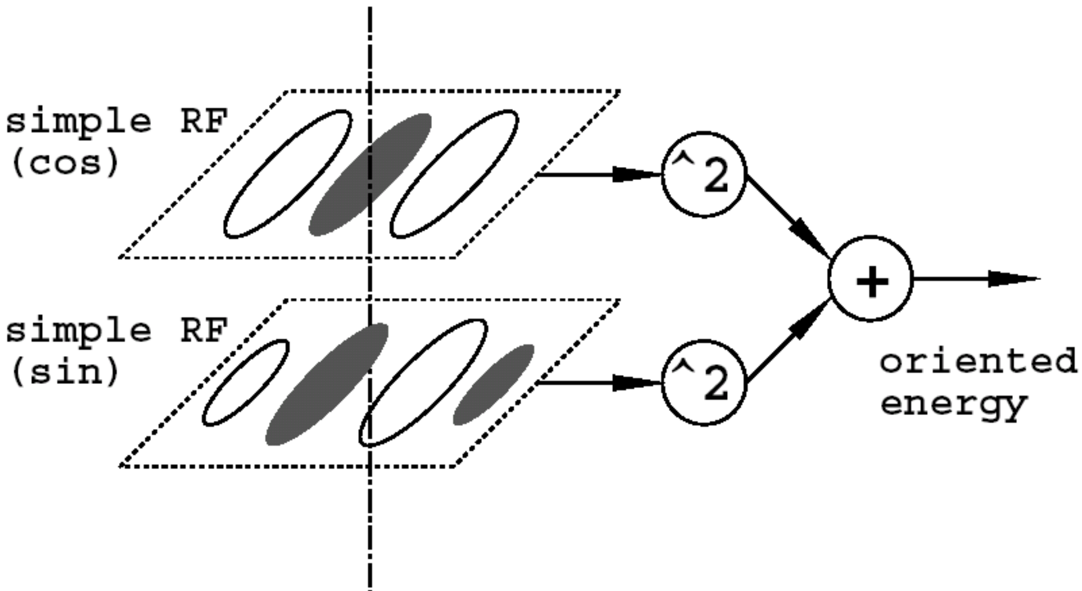
University of British Columbia





Creating features stable to viewpoint change

- Edelman, Intrator & Poggio (97) suggested that complex cell outputs are better for 3D recognition than simple correlation

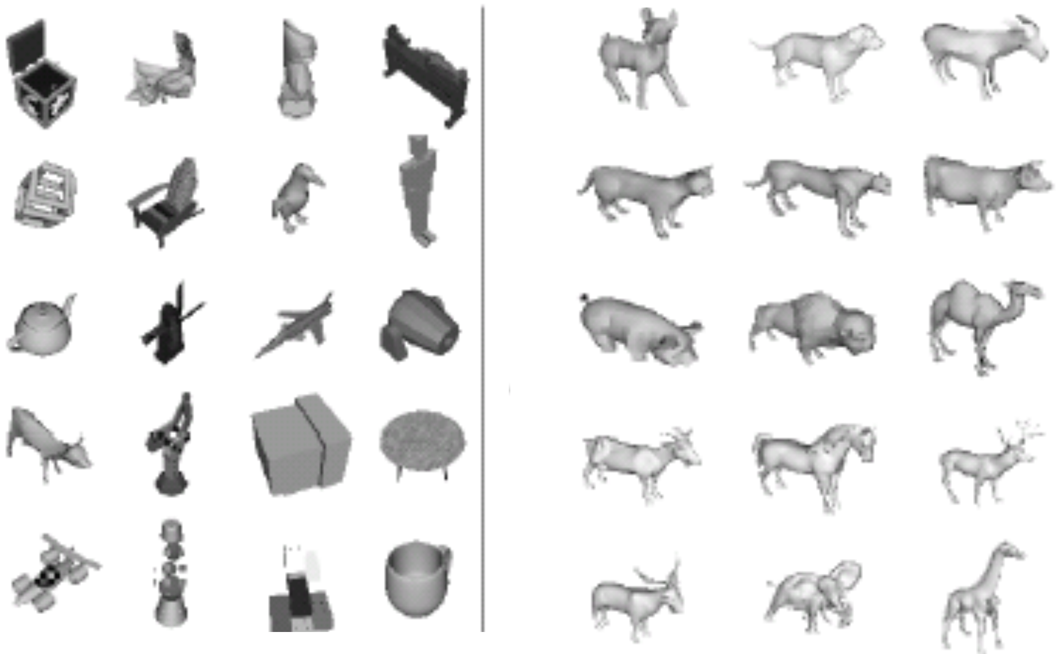


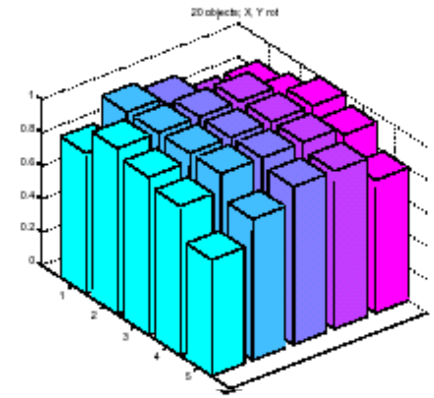
(Edelman, Intrator & Poggio, 97)

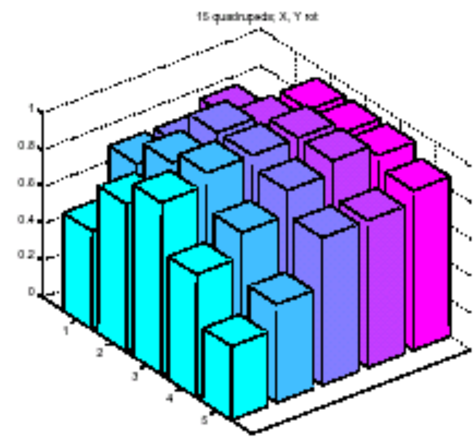
Slide courtesy David Lowe

Stability to viewpoint change

- Classification of rotated 3D models
  - Complex cells: 94% vs simple cells: 35%







(Edelman, Intrator & Poggio, 97)

Slide courtesy David Lowe

SIFT vector formation (Lowe 1999)

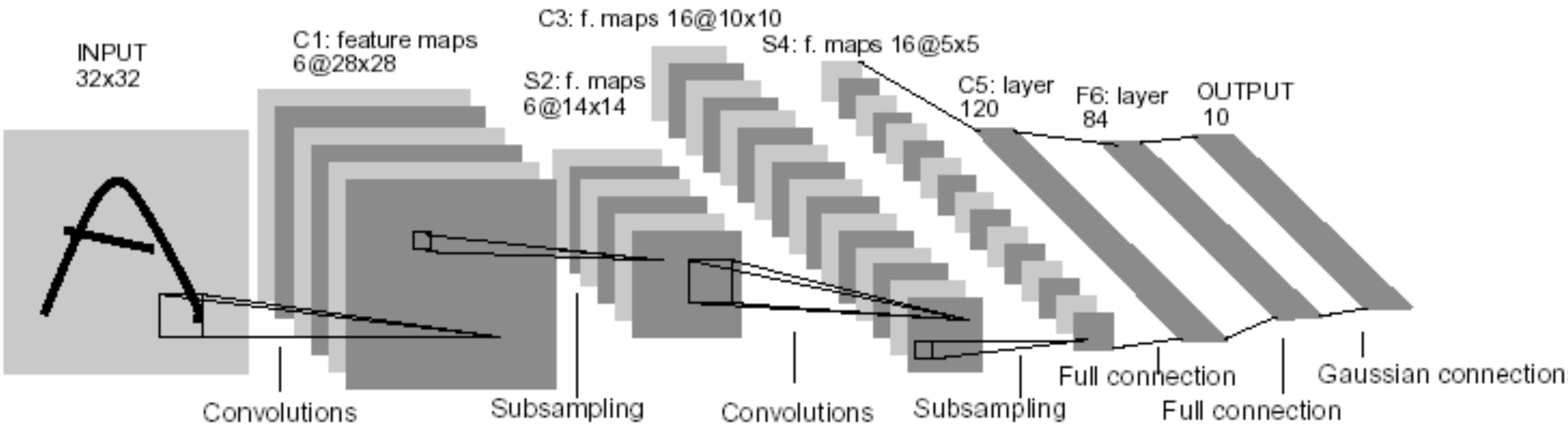
- Rotated image gradients are sampled over 16x16 array of locations in scale space
- Create array of orientation histograms
- 8 orientations x 4x4 histogram array = 128 dimensions

Distinctive image features from scale-invariant keypoints DG Lowe International journal of computer vision 60 (2), 91-110	33017	2004
Object recognition from local scale-invariant features DG Lowe International Conference on Computer Vision, 1999, 1150-1157	10418	1999

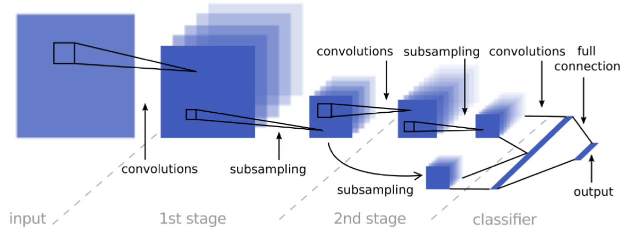
Slide courtesy David Lowe

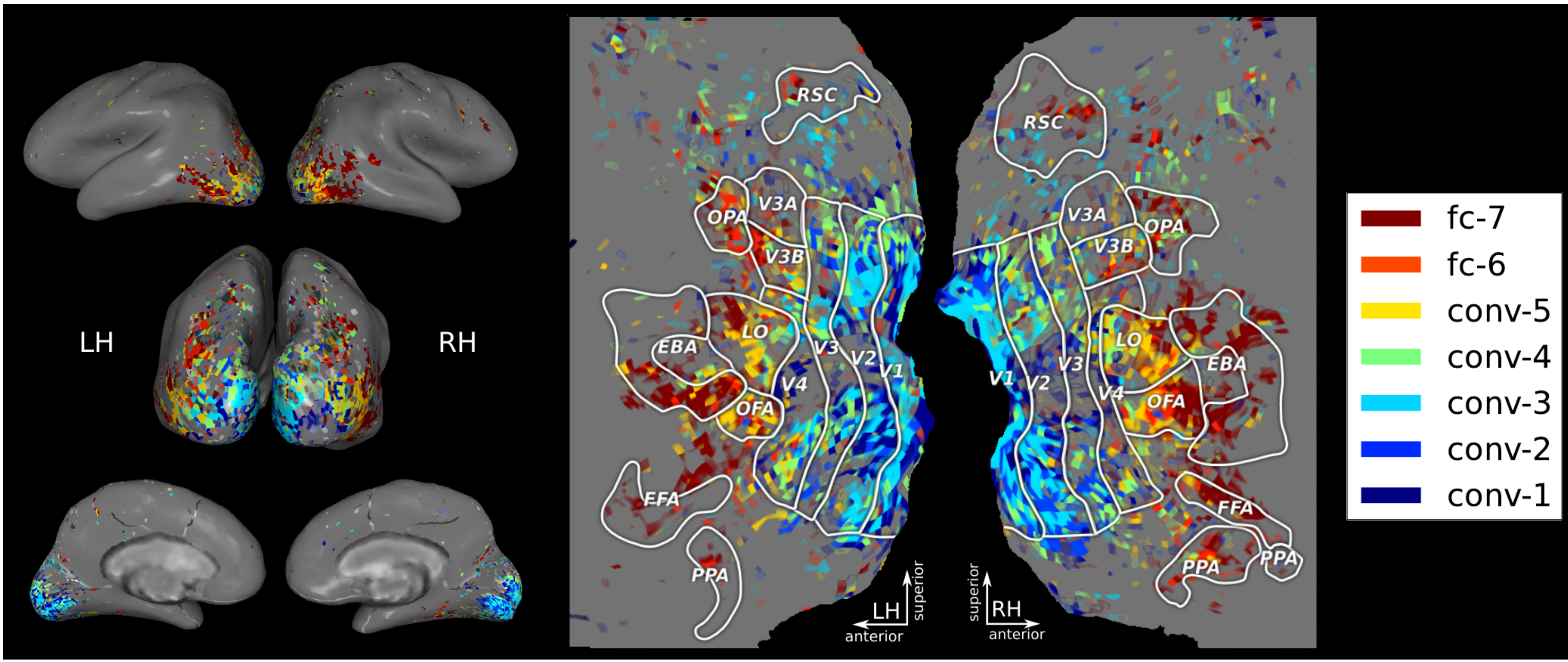
Deep Neural Networks

- Convolutional neural nets are also based on the multistage Hubel-Wiesel architecture (LeCun et al., 1989)



Different levels of Deep Convolutional Neural Networks predict activity in different levels of the visual system





Agrawal, Stansbury, Malik & Gallant, in prep.

COMPUTING

- Computing continues to be our closest "artificial relative" to the brain – how to make it more than "just" a tool:
  - Is there a comprehensive computational theory that can inform our understanding of high-level brain function and the genesis of the mind?
  - How would this theory be expressed and tested?
  - What are the measurable "outputs" of the brain against which such a model could be validated?

FINAL THOUGHTS: ARE THERE DISRUPTIVE VISIONS OF THE FUTURE

- Brain Cartography: What is “Google Maps” for the brain?
  - A complete registry of “places to see and do” for the brain
  - A cor
- Brain Fo   pen-source dynamic
  - Wha
  - How   ?
- Brain Sh   as uploading a photo
  - Data, metadata, and registry

CS AND BRAIN - WHERE DISCOVERY MEETS INVENTION

- It will be impossible to envision brain science absent computational support/theories/models
- This community is under-developed – BRAIN programs are an opportunity to ignite interest and excitement at this juncture
- Learn from other community models – e.g. astrophysics, genomics – to learn what to do (and how to do it well)
- Don't underestimate importance of education and community building!

CHECK OUT THE WEB SITE VIDEOS!

http://cra.org/ccc/events/brain-workshop/

02:45 PM — **Panel: Computing and the Brain**
Shafi Goldwasser
Yann Lecun

07:30 PM — **Plenary: Leslie Valiant, Harvard, Can Models of Computation in Neuroscience be Experimentally Validated?**
Can Models of Co...

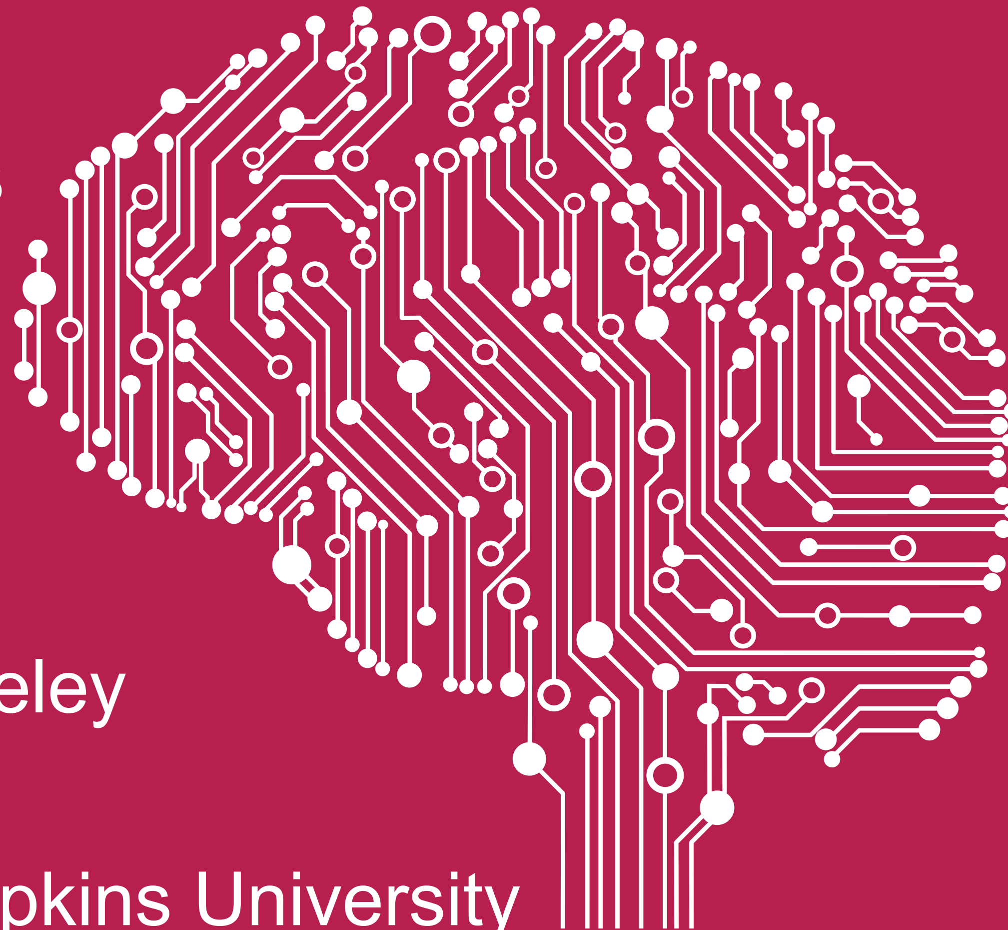
Panel: Creating Open-Science Platforms for Heterogeneous Brain Data
Jeremy Freeman
Greg Farber
Joshua Vogelstein
Sean Hill
Moderator: Miyoung Chun
Creating Open-Sci...

09:30 AM — **Panel: Brain Mapping**
Jeff Lichtman
Charless Fowlkes
Ragini Verma
James Haxby
Moderator: Polina Golland

10:05 AM — **Plenary: Terrence Sejnowski, Salk Institute, Theory, Computation, Modeling and Statistics: Connecting the Dots from the BRAIN Initiative**
Theory, Computati...

02:00 PM — **Plenary: Jack Gallant, UC Berkeley, A Big Data Approach to Functional Characterization of the Mammalian Brain**

Research Interfaces between Brain Science and Computer Science



Jack Gallant, UC Berkeley

Polina Golland, MIT

Greg Hager, Johns Hopkins University

http://cra.org/ccc/events/brain-workshop/

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