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/
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?

• 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 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
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
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.

Cukur & Gallant, 2013
Modha & Singh, 2010

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

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)

\[\tau \ddot{y} = \alpha_z (\beta_z (g - y) - \dot{y}) + f(x) + C_z\]
\[\tau \dot{x} = -\alpha_x x + C_x\]
\[f(x) = \frac{\sum_{i=1}^{k} w_i b_i x}{\sum_{i=1}^{k} w_i} = b^T \phi(x)\]

where
- \(y, \dot{y}\) are the desired position and velocity of a movement
- \(f(x)\) 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.
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
Is neuroscience the “next big data science”?

Table 1: List of useful brain sciences data resources

<table>
<thead>
<tr>
<th>URL</th>
<th>Utility</th>
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<tbody>
<tr>
<td><a href="http://openconnecto.me">http://openconnecto.me</a></td>
<td>Open science data &amp; software</td>
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<tr>
<td><a href="http://www.incf.org/resources/research-tools">http://www.incf.org/resources/research-tools</a></td>
<td>Neuroinformatics tools</td>
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<td><a href="http://web.stanford.edu/group/brainsinsilicon/challenge.html">http://web.stanford.edu/group/brainsinsilicon/challenge.html</a></td>
<td>Dedicated neuromimetic hardware</td>
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<td><a href="https://wiki.humanconnectome.org/display/PublicData/Connecting+to+Connectome+Data+via+AWS">https://wiki.humanconnectome.org/display/PublicData/Connecting+to+Connectome+Data+via+AWS</a></td>
<td>Commercial cloud storage solution for neuroscience</td>
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<td><a href="http://www.birncommunity.org/resources/data/">http://www.birncommunity.org/resources/data/</a></td>
<td>Federal database of certain brain imaging data</td>
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<tr>
<td><a href="http://crcns.org/data-sets">http://crcns.org/data-sets</a></td>
<td>Home-grown brain data repository</td>
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<tr>
<td><a href="http://www.loni.usc.edu/Software/Pipeline">http://www.loni.usc.edu/Software/Pipeline</a></td>
<td>Pipelining software for distributed computing</td>
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<td><a href="http://www.nature.com/sdata/">http://www.nature.com/sdata/</a></td>
<td>Journal dedicated to publishing datasets</td>
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<td><a href="http://www.humanconnectome.org/data/">http://www.humanconnectome.org/data/</a></td>
<td>Publicly shared dataset</td>
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<td><a href="http://fcon_1000.projects.nitrc.org/">http://fcon_1000.projects.nitrc.org/</a></td>
<td>Consortia of publicly shared datasets</td>
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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
• 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
• 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
Edelman, Intrator & Poggio (97) suggested that complex cell outputs are better for 3D recognition than simple correlation.
Stability to viewpoint change

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

(Edelman, Intrator & Poggio, 97)
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

Object recognition from local scale-invariant features
DG Lowe
International Conference on Computer Vision, 1999, 1150-1157

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.
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 connectivity roadmap

• Brain Forecasting: Can we create community, open-source dynamic simulations of brain functions?
  – What can we predict from these models?
  – How are they refined from observational data?

• Brain Sharing: How can data sharing be as easy as uploading a photo on the Web?
  – 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/

<table>
<thead>
<tr>
<th>Time</th>
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<td>09:30 AM</td>
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