Questioning Questions in Computational Neuroscience

Pasta and Profs

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Asking the Right Question Is Critical

Parallel postulate Euclid (circa BC 300) Eugenio Beltrami (1985-1900)
Euclid’s 5th postulate (parallel postulate).

• How can we prove the parallel postulates using ... ?
Unsolvable. Unsolved for thousands of years.

Today’s Topic

• Re-evaluating current questions in (computational) neuroscience.
• Showing how slight change in perspective can lead to new insights.

Euclid’s 5th postulate (parallel postulate).

• How can we prove the parallel postulates using ... ?
Unsolvable. Unsolved for thousands of years.

• How can we prove the parallel postulates using ... ?
Solvable. The answer is “No” (Beltrami)
Background: Current Questions in Neuroscience

1. How is information coded in neural activity?
2. How are memories stored and retrieved?
3. What does the baseline activity in the brain represent?
4. How do brains simulate the future?
5. What are emotions?
6. What is intelligence?
7. How is time represented in the brain?
8. Why do brains sleep and dream?
9. How do the specialized systems of the brain integrate with one another?
10. What is consciousness?

Eagleman, Discover (2007)

Questions to Consider

1. How to understand the neural code?
2. How did consciousness evolve?
3. How does the visual system process texture?
4. How to acquire the connectome? (Time permitting)

Outline
1. How to Understand the Neural Code?

How can we understand the neural code? (X)

How can the brain itself understand its neural code? (O)

Understanding the Neural Code, by the Brain

What do these blinking lights mean?

This is the BRAIN’s perspective.
  – Seems impossible to solve!
Understanding the Neural Code, by Us

• Now we can understand the meaning.
• This is OUR perspective.
  – However, this methodology is not available to the brain!

Sensorimotor Learning to the Rescue

• Property of motor output that maintains internal state invariant
• Same as property of encoded sensory information.

How to Understand the Neural Code?

(a) From the OUTSIDE
(b) From the INSIDE

• How can we understand the brain? (X)
• How can the brain itself understand itself? (O)

Understanding, Inside the Brain
2. How did Consciousness Evolve?

- How did consciousness evolve? (X)
- How did the necessary conditions of consciousness evolve? (O)
2. How did Consciousness Evolve?

- How did consciousness evolve? (X)
- How did the necessary conditions of consciousness evolve? (O)
  - Former is subjective, latter is objective.
  - Predictive dynamics found to be key (Choe et al. 2012).

Necessary Condition for Consciousness

- Are there future events that are 100% predictable?

Necessary Condition for Consciousness

- Are there future events that are 100% predictable?
- What if I say there are such events?
- I will clap my hands in the next 5 seconds.
Necessary Condition for Consciousness

- Are there future events that are 100% predictable?
- What if I say there are such events?
- I will clap my hands in the next 5 seconds.
- “My” actions are 100% predictable, and this (authorship) is a key property of the self, the subject of consciousness.

Thus, the brain dynamics have to be predictable.

Could the Necessary Condition Evolve?

- Simulated evolution.
- Measure predictability of internal state dynamics.

Predictable vs. Unpredictable Internal Dyn.

- Internal dynamics of a simple pole-balancing controller neural network (Kwon and Choe 2008).
Predictable vs. Unpredictable Internal Dyn.

- Performance in controllers with high vs. low internal state predictability (Kwon and Choe 2008).
- Controllers with high ISP better fit in changing environment: Necessary condition can evolve!

Analysis of Real EEG Data

- Awake, REM sleep, and Slow-wave sleep EEG data.
- Inter-Peak Interval (IPI) predictability.


Real EEG Data: Prediction Error

- All differences were significant \( p < 10^{-6} \) except for subject 4, Awake vs. REM.
- Bottom line: Awake and REM more predictable than SWS.


3. How Does the Visual System Process Texture?
3. How Visual System Processes Texture?

• How does the visual system process texture? (X)

• What is the nature of texture? (O)

– Texture is a surface property and is thus tactile.
– Tactile RFs more powerful than visual RFs (Bai et al. 2008; Park et al. 2009).

3. How Visual System Processes Texture?

• How does the visual system process texture? (X)

• What is the nature of texture? (O)

Texture in 2D

• Can you easily see the texture boundary?
Texture in 3D

- Now can you see the boundary?

Preprocessing with Visual vs. Tactile RF

- Preprocess texture with visual vs. tactile receptive field.
- Run classifier on result.

Tactile vs. Visual Texture Processing

- Tactile filter better than visual filter (Bai et al. 2008).
- Texture may be more intimately related to touch.

Natural Scene: Texture = Visual:Tactile

- Train identical cortical devel. model w/ (1) natural scene and (2) texture.
- (1) leads to visual RFs. (2) Leads to tactile RFs.

Park et al. IEEE CIMSVP 2010
4. How to Acquire the Connectome

- How to acquire the connectome? (X)
- What if the connectome is available today? (O)

- Test analysis methods with synthetic connectome.
What if Connectome is Available Today?

- *C. elegans* connectome is available (White et al. 1986).
  - Without activity and behavior data, progress is slow.
- Izquierdo and Beer (2013): used genetic algorithm to search for the parameters.
- Sohn et al. (2011): used cluster analysis to identify functional modules.

Analysis of the Connectome

- Neuroimaging-based
  - Park et al. (2014): Used graph-ICA to identify task-specific subnetworks.
- EM-level connectome
  - Seung and Sümbül (2014): Cell types, connectivity, and function (direction selectivity) in the retina.

Synthetic Connectomics

- Simulated evolution of neural network controllers.
- Use a topological evolution algorithm (NEAT, Stanley and Miikkulainen 2002).
- Full access to connectivity, weight, activity, and behavior.

Example: Analyze This!

- Simple circuit evolved using Neuroevolution (NEAT).
  - Hard to know what it does without sensorimotor linkage: Brain in a vat.
Example: Context

- Task: Navigation to goal.
- Input: fixed input (bias) and angle to goal.
- Output: thrust and angle adjust.

Approach: Lesion Study

- Observe behavior after eliminating connections or neurons.
- Result: works well with almost everything gone!
  - Need to study behavior in a social context to fully understand circuit function.

Example 2: Tool Use

- Articulated arm.
- Tool (green bar) pick up and reach goal.
- Evolved neural network controller.

Evolved Circuits: $S^2T$

- Complexity depends on fitness criterion used.
Evolved Circuits: DS

- Complexity depends on fitness criterion used.
- How can we analyze these circuits?

Tool Use Behavior

- Articulated arm.
- Tool (green bar) pick up and reach goal.

Performance

- D: distance, S: speed, T: tool pick up frequency
- Decent performance, better with “T”.

Tool Use Behavior: Various Patterns

- Successful
- Unsuccessful

S: start, T: pick up tool, E: end
How to Understand the Evolved Networks?

- Analyze recurrent loops (cycles in the connectivity).
- Clustering of activation dynamics.
- Correlated behavior and activation dynamics.
- Mostly preliminary work at this point.

Importance of Recurrent Connections

- Faster evolution (top), more compact networks (bottom).

Recurrent Loops vs. Performance

- Number of loops positively correlated with performance.

Example Network

- A representative successful network.
Activation of Neurons and Behavior

Synthetic Connectomics Techniques to be Explored

• Behavior categorization
• Internal dynamics categorization
• Systematic lesion studies and causality analysis
• Individual vs. social context comparison
• Circuit module identification through phylogenetic profiling
• Task-circuit mapping through black-box transfer learning

Discussion: More Questions

• How are memories stored and retrieved? (X)
  – Assumes memory is about the past.
  – Assumes that memory is internal.
• How are memories used to predict? (O)
  – Memory is for the future (Lim and Choe 2006b, 2005, 2006a, 2008).
• How are the processings of internal and external memory related? (O)
  – Memory can be inside AND outside (Chung and Choe 2011).

Discussion and Conclusion
Discussion: Yet More Questions

- How does the brain process information? (X)
  - Information has meaning only relative to an observer.
  - Shannon’s information: No semantics, by definition.
- How does the brain process meaning? (O)
  - Meaning/semantics should be inherent to the brain.
- How does the brain optimize speed/accuracy/quantity? (X)
- How does the brain optimize quality? (O)

Acknowledgments

- Neural coding: Bhamidipati (2004); Choe and Bhamidipati (2004); Choe and Smith (2006); Choe et al. (2007); Choe (2011); Choe et al. (2008)
- Consciousness: Kwon and Choe (2008); Choe et al. (2012); Chung et al. (2012)
- Texture: Bai et al. (2008); Park et al. (2009); Bai (2008); Park (2009)

Conclusion

- Taking the brain’s own perspective.
- Reducing to tractable, objective necessary conditions.
- Questioning the nature of things.
- Do we have powerful enough tools, if full data is given?

References


