In Transition

• from Part I: Basic Mechanisms.

• to Part II: Perception, Attention, Memory, Language, Higher Level.

Cognition
Summary of Part I: Basic Mechanisms
Micro and Macro-Neurocomputomics

Micro = basic mechanisms common across brain areas.
Macro = organization, differentiation, interactions of brain areas.

Before we can think about larger cognitive functions, need to consider general principles for macro organization and interaction of brain areas.
Macro Structural Principles

Pathway 1
• Hierarchical sequence of transformations.

Pathway 2

\begin{itemize}
  \item Emphasize some distinctions, ignore others.
  \item For object recognition you want to ignore differences in location, lighting, size, rotation.
  \item When reaching for objects, you want to emphasize location, size.
\end{itemize}
Macro Structural Principles

- Specialized pathways.

  Location/orientation but cannot perceive them:
  - Patients with ventral stream damage have blindsight (e.g., Milner & Goodale 1995): they can reach and grasp objects at different locations/orientations but cannot perceive them.
  - Location for actions (seeing for identifying and seeing for action vs. recognizing orientation)
  - Location-invariant object recognition vs. recognizing orientation

Pathway 1

Pathway 2
Macro Structural Principles

Pathway 1

• Inter-pathway interactions.

Pathway 2

Visual attention is an emergent property of interactions between object identification & spatial pathways.

Macro Structural Principles
Macro Structural Principles

Pathway 1

Pathway 2

Higher-level association areas

At extreme, thought to underlie synesthesia – Integration of e.g., visual and auditory information
Large-scale Distributed Representations

- Same idea as distributed representation among units for individual items, but just now across multiple areas/modalities, etc.
- Each area represents multiple things
- Multiple areas participate in representing a given thing (e.g., apple)
- Knowledge is distributed across multiple brain areas

Macro Structural Principles
Macro Dynamic Principles

• Processing as multiple constraint satisfaction

• Attractors, settling dynamics, amplification; active memory

• Inhibitory competition: attention

Where do constraints come from?
Macro Dynamic Principles

- Where do constraints come from?
  - Perceptual inputs ("bottom-up" constraints)
  - Also, we have the ability to maintain firing of neurons even in the absence of bottom-up stimulation
  - Make use of bidirectional excitatory connections
  - Active memory – constitutes an inner mental context

Where do constraints come from?
Macro Dynamic Principles

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- Perceptual inputs ("bottom-up" constraints)

where do constraints come from?

Active memory ← constitutes an inner mental context

- Make use of bidirectional excitatory connections

absence of bottom-up stimulation

- Also, we have the ability to maintain firing of neurons even in the

She walked from the post office to the bank.
She swam from the overturned canoe to the bank.
Macro Dynamic Principles

• Where do constraints come from?

Active memory can pertain to concrete stimulus representations as well as more abstract things.

Active memory ← constituents an inner mental context

Make use of bidirectional excitatory connections

abscence of bottom-up stimulation

Also, we have the ability to maintain firing of neurons even in the perceptual inputs (bottom-up constraints)

Where do constraints come from?
General Functions of the Cortical Lobes

Frontal Lobe: Motor control, cognitive control (planning, working memory, etc)

Parietal Lobe: Representing body & external spaces

Temporal Lobe: Hearing, speech perception, object recognition...

Occipital Lobe: Vision
Other Areas

• Hippocampus (rapid episodic encoding).
• Thalamus (sensory input, attention).
• Amygdala (emotion, affective associations).
• Basal ganglia (BG) (motor control, sequencing, reward learning, gating).
• Midbrain neuromodulators: VTA - dopamine, raphe - serotonin, locus ceruleus - norepinephrine.
• Cerebellum (motor learning, forward model, cognitive role via timing?).
• Other Areas...
Tripartite Functional Organization

Defined by set of functional trade-offs:

PC = prefrontal cortex: active maintenance ("working memory");

HC = hippocampus and related structures: rapid memorization;

PC = posterior perceptual cortex: slow integrative learning.
Defined by set of functional trade-offs.
Multiple systems in decision making
Computational trade-offs in learning & memory

Trade-offs:

Robust maintenance vs. rapid updating

→ Begin to address psychological distinctions between different learning & memory processes, informed by mechanisms required.

• Learning statistical structure vs. memorizing specific events

• Isolated maintenance (holding in mind multiple items of info) vs. inference (spreading activation: smoke → fire)

→ This cannot be achieved by a single brain system.

Computational trade-offs in learning & memory
1. Slow vs Fast Learning

Learning must be slow to capture (statistical) structure (averaging).

But you also have to be able to learn rapidly.

Tradeoff solved by 2 systems: cortex learns slowly, hippo rapidly.
1. Slow vs Fast Learning

Learning must be slow to capture (statistical) structure (averaging).

But you also have to be able to learn rapidly.

**Tradeoff solved by 2 systems:**
- Hippo: learns slowly
- Cortex: learns rapidly
- Active memory (prefrontal cortex) is fastest (immediately accessible)

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**Graph:**
- Lrate = 0.05
- Lrate = 0.1
- Lrate = 1

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![Graph](image-url)
Learning must be slow to capture (statistical) structure (averaging).

But you also have to be able to learn rapidly.

Tradeoff solved by 3 systems: cortex learns slowly, hippo rapidly.

But learning to develop pfc reps in first place is slow, allows abstraction.

3rd system: Active memory (prefrontal cortex) ≈ fastest (immediately accessible)
[Reinforcement] Learning must be slow to capture best actions that work on average.

BC learns slowly, PFC flexibly updates new states and can override habitual choices.

But you also have to be able to sensitive to rapid changes in value (e.g., stock market).

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1b. Slow vs Fast [Reinforcement] Learning
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[Reinforcement] Learning must be slow to capture best actions that work on average. But you also have to be able to sensitive to rapid changes in value (e.g., stock market).

[Reinforcement] Learning is solved by 2 systems: BG learns slowly, PFC flexibly updates new states and can override habitual choices.

→ lots of evidence for differential BG and PFC contributions to habitual and rapid action-outcome learning, across species, methods.
Overlapping distributed representations are useful for capturing information about the world. But overlap & interconnectivity cause spread, which is not useful for maintaining specific information over time. Tradeoff solved by two systems: PC has overlapping distributed representations, FC is isolated for maintenance.
Basal ganglia may contribute to this updating function.
4. Model-Based vs. Model-Free RL

Model-based (Cognitive)

- Actually represent the environment (world-model) and predicted transition from one state to another, and how these are affected by our (and others') actions...

- Incrementally learn to associate stimuli (states) and actions with value (or Go-NoGo value), select action with highest "Q value" (or Go-NoGo value), update values (TD learning and variants thereof; BG model). Then just use only (DA-based) reward prediction errors to update value, learning only (DA-based) reward prediction errors to update value, using only (DA-based) reward prediction errors to update value, using only (DA-based) reward prediction errors to update value.

Model-free (Habits)

- Model-free vs. Model-Free RL (not in text)
Devaluation Experiment

1. Training: "Training" text is not clearly visible.

2. Non-devalued: "Non-devalued" text is not clearly visible.

3. Test: "Test" text is not clearly visible.

4. Expiration: "Expiration" text is not clearly visible.

5. Motivational Shift: "Motivational Shift" text is not clearly visible.

6. Hungry: "Hungry" text is not clearly visible.

7. Sated: "Sated" text is not clearly visible.

8. Don't want: "Don't want" text is not clearly visible.

9. Food they work for: "Food they work for" text is not clearly visible.

10. Will animals: "Will animals" text is not clearly visible.
Holland (2004)

Repetition became automatic with wall training. Then animals will sometimes work for food they don't need.

Like Tolman

Like S-R (Thom dislike)

"Habitual"

outcome-insensitive

outcome-sensitive

Moderate training

Tolman

Depleted

Non-depleted

Behavioral Results

3. test

2. devaluation

1. training

(thungy)

(ducky)
Yin et al. (2004)

- corticostriatal loop
division of PFC (same
dopamine
also lesions to infralimbic
also treatments depleting
extensive training
ever develop habits despite
dorsolateral striatum (DG)
animals with lesions to

Lesion Results

- dorsal lateral

<table>
<thead>
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<th>Condition</th>
<th>% of final response rate</th>
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<td>0.8</td>
</tr>
<tr>
<td>Developing</td>
<td>0.5</td>
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</table>

overtrained rats

Lesion (sham lesion) control
dorsolateral
Double dissociation with IL PFC
also dorsomedial PFC and medioventral thalamus (same loop)
only moderate training

Primiparic (PL) PFC lesions cause animals to leverpress habitually even with


Lesion Results
What do these findings tell us?

- The same action (lever-pressing) can arise from two psychologically & neuronally dissociable pathways (see also BG vs Hippo in S-R vs cognitive map).

- Lesions suggest two parallel systems, in that the intact one can apparently support behavior at any stage. (see also BG vs Hippo in S-R vs cognitive map)

- Overtrained behavior is habitual: apparently not dependent on outcome representation of what might happen.

- Moderately trained behavior is goal-directed: dependent on outcome, like S-R learning.

- S-R habits really exist (in humans too), they just don't describe all of behavior.

- Lesions suggest two parallel systems, in that the intact one can apparently support behavior at any stage. (see also BG vs Hippo in S-R vs cognitive map)
Strategy: Model-based RL

1. Search through map
2. Compute Q values by iteration
3. Experience (cognitive map)
4. Learn model of task through

Choosing actions is hard (need to...
(recompute values online)

but flexible, efficient representation

experience (= cognitive map)

learn model of task through

Strategy 1: Model-based RL
- Dopamine dependent TD learning
- Incremental "samplings and prediction errors
- Can learn these from experience
- Without building or searching a model
- Then simply retrieve them to choose action
-Shortcut: store long-term values

Strategy II: Model-free RL
Summary: Model-based vs Model-free RL

Instrumental conditioning reveals that rats indeed have S-R habits (and humans, Tricomi et al., 2009) but even humble rat is cognitive: must distinguish habits from goal-directed behaviors. For computational models of these and related phenomena, including how the brain might arbitrate between the two systems, see Daw, Niv & Dayan (2005) and Frank & Claus (2006).

Note: same overt behavior can be the product of different neural (computational) systems involved (BG, PFC, HC...). Understand this distinction algorithmically in terms of functional properties of biological decision making, and mechanistically in terms of functional properties of biological strategies for different RL algorithms.

But even humble rat is cognitive: must distinguish habits from goal-directed behaviors. For computational models of these and related phenomena, including how the brain might arbitrate between the two systems, see Daw, Niv & Dayan (2005) and Frank & Claus (2006).

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Reinforcement Learning: Dopamine can reinforce rewarding actions so that they are more likely to be executed in the future.

But what if other possible actions are even better? How would you ever know?

This allows an agent to exploit the best possible actions in a situation that are most likely to lead to reward.
Reinforcement learning: Dopamine can reinforce rewarding actions so that they are more likely to be executed in the future. Norepinephrine (NE) modulates the noise in cortical representations, allowing an agent to sometimes randomly select some other action.  

But what if other possible actions are even better? How would you ever know?

See Aston-Jones & Cohen, 2005, Ann Rev Neurosci; 5. Exploration vs Exploitation (not in text);
Two modes of LC firing:

- **Tonic**: high baseline firing
  - Effectively adds noise, **RT variability** (Usher et al., 1999)
  - High tonic mode during poor performance
  - High baseline firing
  - Poor task performance

- **Phasic**: low tonic, but high evoked firing
  - Facilitates response execution and **exploitation**
  - Phasic mode observed: focused attention, interoceptive target detection
  - Supports **exploration** of new behaviors (McClure et al., 2005)

Two modes of LC firing:

LC and Norepinephrine
Usher et al., 1999
Usher et al., 1999 Model of LC
Aston-Jones & Cohen (2005)

• Phasic NE facilitates response execution

• Tonic NE enhances noise, reps of multiple actions for exploration.

LC/NE effects: Adaptive Gain
LC tonic/phasic mode under top-down control

When actions no longer rewarding, NE system responds by increasing noise and exploration of new actions. See McClure et al. 2005 for model.
ADHD: NE dysfunction?

- Consistent finding of increased RT variability in ADHD
- Responsive to medications that modulate NE
- Also evidence for reduced BG/DA
- Also exploration?
ADHD: NE dysfunction?

Data Model

Condition

<table>
<thead>
<tr>
<th>30</th>
<th>40</th>
<th>50</th>
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Percent Switching

Controls / LC Phasic

ADHD / LC Tonic

Trial-to-trial Switching / Exploration: Dysfunctional NA?

0 20 40 60 80 100

normalized RT Variability (%)

Switching and RT Variability

non-medicated ADHD

Frank, Santamaria, O'Reilly & Willcutt (2007)

Also: NE (but not DA) metabolites in urine correlated w/ RT variability in ADHD

(Llorente et al., 2006)
The functional architecture of the brain reflects the need to simultaneously achieve multiple, computationally incompatible objectives.

To avoid making trade-offs we have evolved specialized structures that are compatible with neurobiological and behavioral data (that are)

The process of trying to build computational models helps us identify these trade-offs.

The functional architecture of the brain reflects the need to simultaneously achieve multiple, computationally incompatible objectives.

Summary
Challenges

• Networks are good at some things, but have problems with others.

• Nobody's perfect: People tend to be bad at some things networks are.

• Don't throw the baby out w/the bathwater!
The Binding Problem
The Binding Problem: Potential Solutions

• Nobody's perfect: people make tons of binding errors.

• Dynamic synchrony: things that fire together go together.

• Separately represented.

• Encode conjunctions: no need to have all possible conjunctions.

• Attention: only focus on one item.

• Encode conjunctions: no need to have all possible conjunctions.
Other General Problems

• Representing multiple instances of the same thing (attention + counting, location)

• Comparing representations

(PMC-PFC)

(overlap - multiple digits, settling in shared weights - goodness)

(attention + counting, location)

Representing multiple instances of the same thing

• Nobody's perfect...
Recursion and Subroutine-like processing

- In middle of processing, need to perform same processing (recursion) or different processing (subroutine).
- Easy in standard serial computer (store current state, call subroutine w/appropriate arguments)
- Harder when data and processing not separated!
- HCMP, PEC
- Nobody’s perfect...

The mouse the cat the dog bit chased squeaked.

Recurision and Subroutine-like processing
Generalization

How to recognize new inputs given dedicated, specialized reps?

• Distributed representations: combinations of existing features.
• Abstraction: learn that all dogs might bite, not just that spike bit me.
• Nobody’s perfect: Transfer is not good at all.
Important Distinctions

- Controlled vs Automatic Processing.
- Declarative/Procedural vs Explicit/Implicit.
- Consciousness vs Influence (on Constraint Satisfaction):
  - Centrality: more influence on other areas.
  - Duration: longer = more influence.
  - Intensity: higher = more influence.

Controlled vs Automatic Processing.
A Cognitive Architecture