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## In Transition

- from Part I: Basic Mechanisms.
- to Part II: Perception, Attention, Memory, Language, Higher Level Cognition

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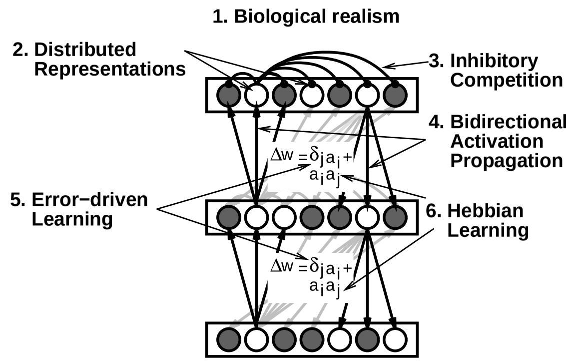
## Summary of Part I: Basic Mechanisms

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## Micro and Macro-Neurocomputomics

Micro = basic mechanisms common across brain areas.

Macro = organization, differentiation, interactions of brain areas.

*Need to consider general principles for macro organization before we can think about larger cognitive functions.*

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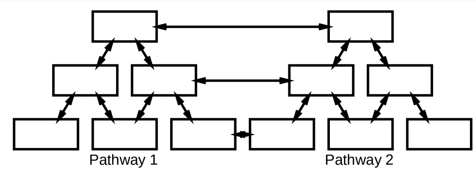
## Macro Structural Principles




- Hierarchical sequence of transformations.
  - Emphasize some distinctions, ignore others
  - For object recognition you want to ignore differences in location, lighting, size, rotation
  - When reaching for objects, you want to emphasize location, size, and ignore object identity

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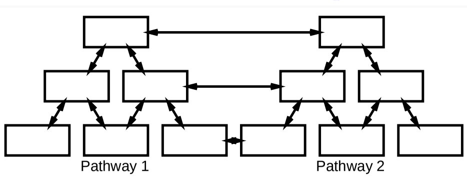
## Macro Structural Principles




- Specialized pathways.
  - Location-invariant object recognition vs. recognizing orientation & location for actions (seeing for identifying and seeing for action)
  - 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!

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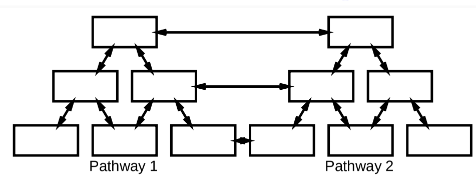
## Macro Structural Principles




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

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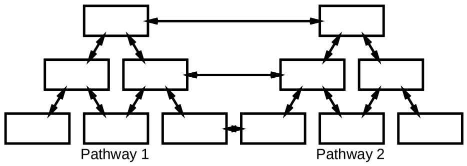
## Macro Structural Principles




- Higher-level association areas
  - Integration of e.g., visual and auditory information
  - At extreme, thought to underlie *synesthesia*

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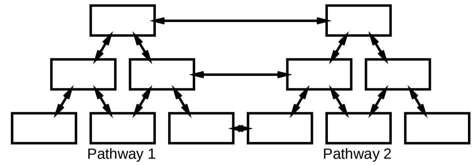
## Macro Structural Principles




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

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## Macro Dynamic Principles

- Processing as **multiple constraint satisfaction**
- Attractors, settling dynamics, amplification
- Inhibitory competition: attention.
- Where do constraints come from?

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## 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*

*She swam from the overturned canoe to the bank.*
*She walked from the post office to the bank.*

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

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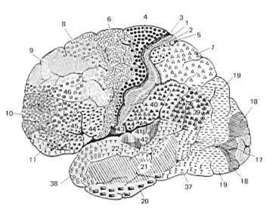
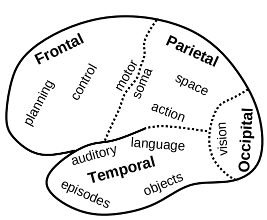
## General Functions of the Cortical Lobes






- Occipital lobe: vision
- Temporal lobe: hearing, speech perception, object recognition
- Parietal lobe: representing body & external spaces
- Frontal lobe: Motor control, cognitive control (planning, working memory, etc)

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## Other Areas

- Hippocampus (rapid episodic encoding).
- Thalamus (sensory input, attention).
- Amygdala (emotion, affective associations).
- Basal ganglia (BG) (motor control, sequencing, reward learning, gating of PFC...).
- Cerebellum (motor learning, cognitive role via timing?).
- Midbrain neuromods: VTA - dopamine, raphe - serotonin.

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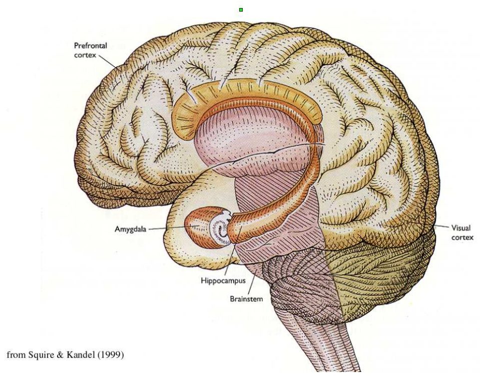


from Squire & Kandel (1999)

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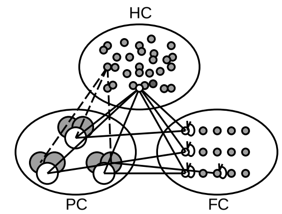
## Tripartite Functional Organization




PC = posterior perceptual cortex: *slow integrative learning*

HC = hippocampus and related structures: *rapid memorization*

FC = prefrontal cortex: *active maintenance ("working memory")*

Defined by set of functional *trade-offs*.

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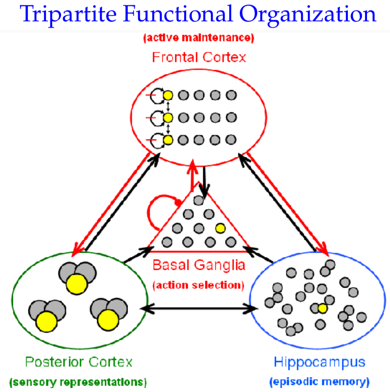
## Tripartite Functional Organization




Defined by set of functional *trade-offs*.

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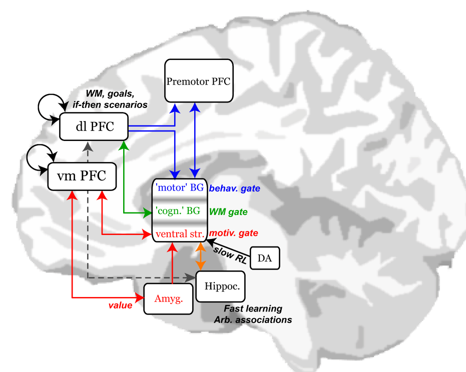
## Multiple systems in decision making

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## Computational Trade-offs in Learning & Memory

Trade-offs: Computational objectives that are mutually incompatible and thus cannot be achieved by a single brain system.

→ 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)*
- *Robust maintenance* vs. *rapid updating*

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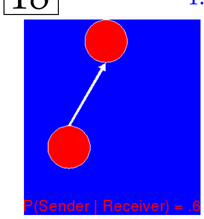
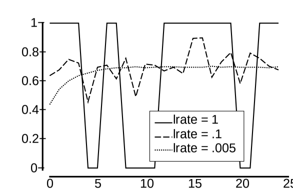
## 1. Slow vs Fast Learning



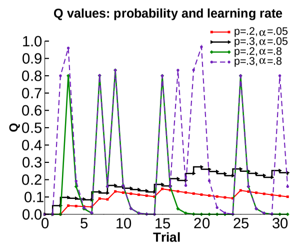

Learning must be *slow* to capture (statistical) structure (averaging).

But you also have to be able to learn rapidly.

*Tradeoff* solved by 2 systems: cortex learns slowly, hippo rapidly.

3rd system: Active memory (prefrontal cortex) ≈ fastest (immediately accessible) *but learning to develop pfc reps in first place is slow, allows abstraction.*

## 19 1b. Slow *vs* Fast [Reinforcement] Learning



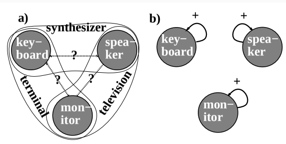

[Reinforcement] Learning must be *slow* to capture best actions that work on average.

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

*Tradeoff* 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.

## 20 2. Active Memory *vs* Overlapping Distributed Reps




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.

## 21 3. Active Memory: Another Trade-off

Active memory needs specialized updating & maintenance mechs.

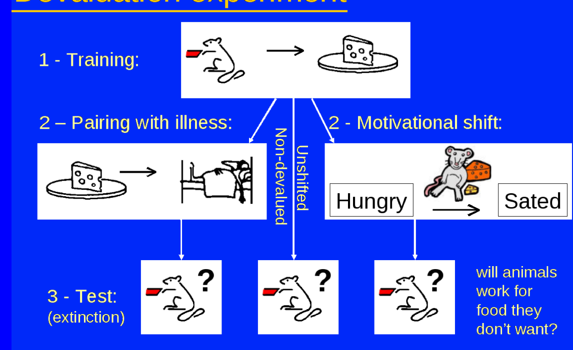
Protecting representations from interference (robust maintenance of working memory) vs. being receptive to update important, unexpected information

Basal ganglia may contribute to this updating function

## 22 4. Model-Based vs. Model-Free RL (not in text)

- *Model-free: (Habits)*
  - Incrementally learn to associate stimuli (states) and actions with value, using only (DA-based) reward prediction errors to update values (TD learning and variants thereof). Then just select action with highest *"Q value"* at any point.
- *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....

## 23 Devaluation experiment



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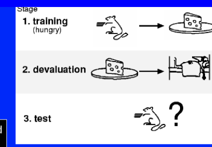
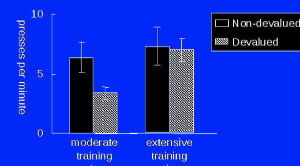
# Behavioral results




outcome-sensitive
“goal-directed”
like Tolman

outcome-insensitive
“habitual”
like S-R (Thorndike)

Animals will *sometimes* work for food they don't want!

→ in daily life: actions become automatic with repetition

Holland (2004)

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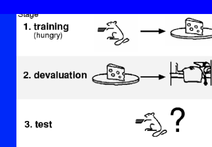
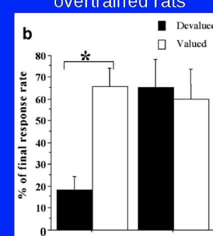
# Lesion results I




overtrained rats




dorsolateral striatum lesion

control (sham lesion)

animals with lesions to dorsolateral striatum (BG) never develop habits despite extensive training
→ also treatments depleting dopamine
→ also lesions to infralimbic division of PFC (same corticostriatal loop)

Yin et al (2004)

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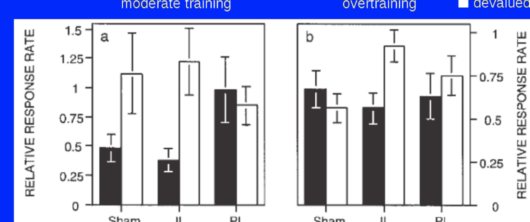
# Lesion results II

moderate training

overtraining

control
devalued




Killcross & Coutureau (2003)

Prelimbic (PL) PFC lesions cause animals to leverpress habitually even with only moderate training
→ also dorsomedial PFC and mediodorsal thalamus (same loop)
→ double dissociation with IL PFC

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## What do these findings tell us?

- The same action (lever-pressing) can arise from two psychologically & neurally **dissociable** pathways
  - moderately trained behavior is ***goal-directed***: dependent on outcome representation of what might happen
  - overtrained behavior is ***habitual***: apparently not 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)

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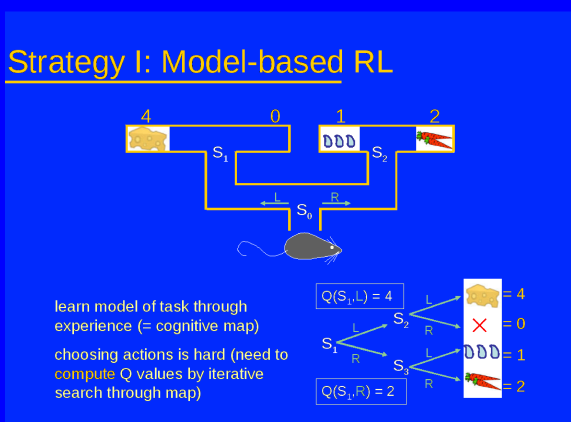


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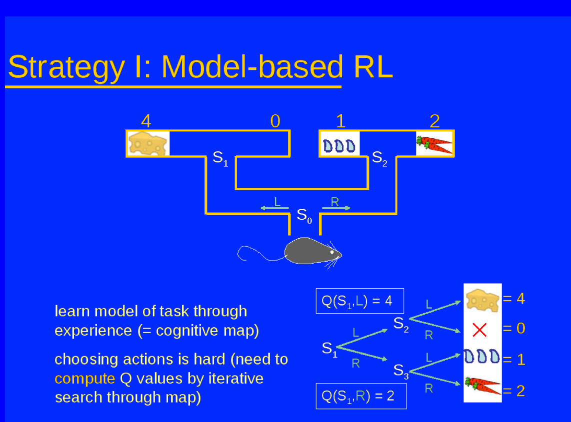
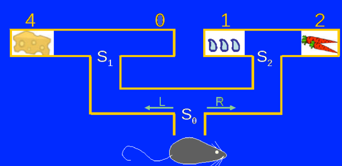
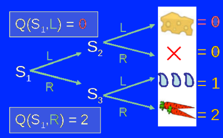


## Strategy I: Model-based RL




learn model of task through experience (= cognitive map)

but flexible, efficient representation (recompute values online)

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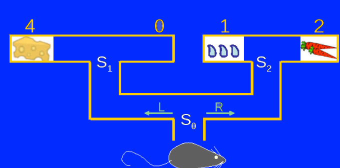
## Strategy II: Model-free RL




- Shortcut: store long-term values
  - then simply retrieve them to choose action
- Can learn these from experience
  - without building or searching a model
  - incremental "sampling" and prediction errors
  - dopamine dependent TD learning

Stored:

$Q(S_0,L) = 4$
$Q(S_0,R) = 2$

$Q(S_1,L) = 4$
$Q(S_1,R) = 0$

$Q(S_2,L) = 1$
$Q(S_2,R) = 2$

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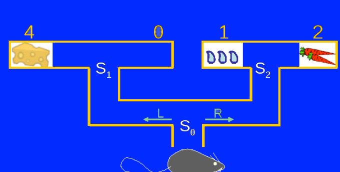
## Strategy II: Model-free RL




choosing actions is easy so behavior is quick, reflexive (S-R)

but inflexible, need relearning to adapt to any change (habitual)

Stored:

$Q(S_0,L) = 4$
$Q(S_0,R) = 2$

$Q(S_1,L) = 4$
$Q(S_1,R) = 0$

$Q(S_2,L) = 1$
$Q(S_2,R) = 2$

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## 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
- understand this distinction ***algorithmically*** in terms of different RL strategies for decision making, and ***mechanistically*** in terms of functional properties of biological systems involved (BG and PFC)
- note: ***same*** overt behavior can be the product of ***different*** neural (computational) systems (controllers)
- 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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## 5. Exploration vs Exploitation (not in text); See Aston-Jones & Cohen, 2005, Ann Rev Neurosci

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

This allows an agent to *exploit* the best possible actions in a situation that are most likely to lead to reward

But what if other possible actions are even better? How would you ever know? *Norepinephrine (NE)* modulates the *noise* in cortical representations, allows agent to sometimes randomly select some other action. This NE system is itself controlled by overall *long term utility*, so that when previous actions no longer rewarding over extended period of time, NE system responds by increasing noise and exploration of new actions.

Also: "Directed" exploration, e.g. toward uncertain options (optimistic)

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## Summary

- 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
- The process of trying to build computational models (that are compatible with neurobiological and behavioral data) helps us identify these trade-offs

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## Challenges

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

- Nobody's perfect: People tend to be bad at same things networks are..
- Don't throw the baby out w/the bathwater!

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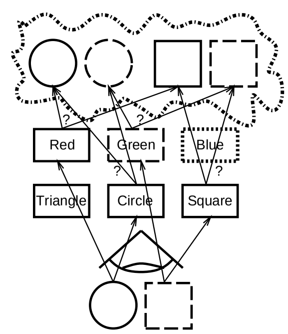
## The Binding Problem

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## The Binding Problem: Potential Solutions

- Attention: only focus on one item.
- Encode conjunctions: no need to have all possible conjunctions separately represented.
- Dynamic synchrony: things that fire together go together.
- Nobody's perfect: people make tons of binding errors..

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## Other General Problems

- Representing multiple instances of the same thing (attention + counting, location)
- Comparing representations (overlap – multiple digits, settling in shared weights – goodness, PMC-PFC)
- Nobody's perfect...

## 40 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, PFC
- Nobody's perfect...
  The mouse the cat the dog bit chased squeaked.

## 41 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..

## 42 Important Distinctions

- Controlled *vs* Automatic Processing.
- Declarative/Procedural *vs* Explicit/Implicit.

Consciousness = influence (on Constraint Satisfaction):

- Centrality: more influence on other areas.
- Duration: longer = more influence.
- Intensity: higher = more influence.

## 43 A Cognitive Architecture