Exploring Neural Mechanisms for Prediction

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Prediction: Essential for Action and Cognition

i of the Vortex: From Neurons to Self. Llinas, 2001

- You only need a brain if you **move**
- The faster and more intricate the moves, the more you need to **predict** their outcomes, since sensory processing is slow.

On Intelligence. Hawkins, 2004

> *Intelligence and understanding started as a memory system that fed predictions into the sensory stream. These predictions are the essence of understanding. To know something means that you can make predictions about it... We can now see where Alan Turing went wrong. Prediction, not behavior, is the proof of intelligence.*

Cognitive Incrementalism

Llinas (pg. 35)

> *...that which we call thinking is the evolutionary internalization of movement..*

Mindware (pg. 135), Andy Clark, 2001

> *This is the idea that you do indeed get full-blown human cognition by gradually adding bells and whistles to basic (embodied and embedded) strategies of relating to the present at hand.*

- Is the predictive machinery evolved for motion also used for cognition?
- Could it be the basis of *common sense*?
- Is it the key to Artificial General Intelligence (AGI)?

Predict

- To **declare** or **indicate** in advance
- To foretell on the basis of observation

Declare

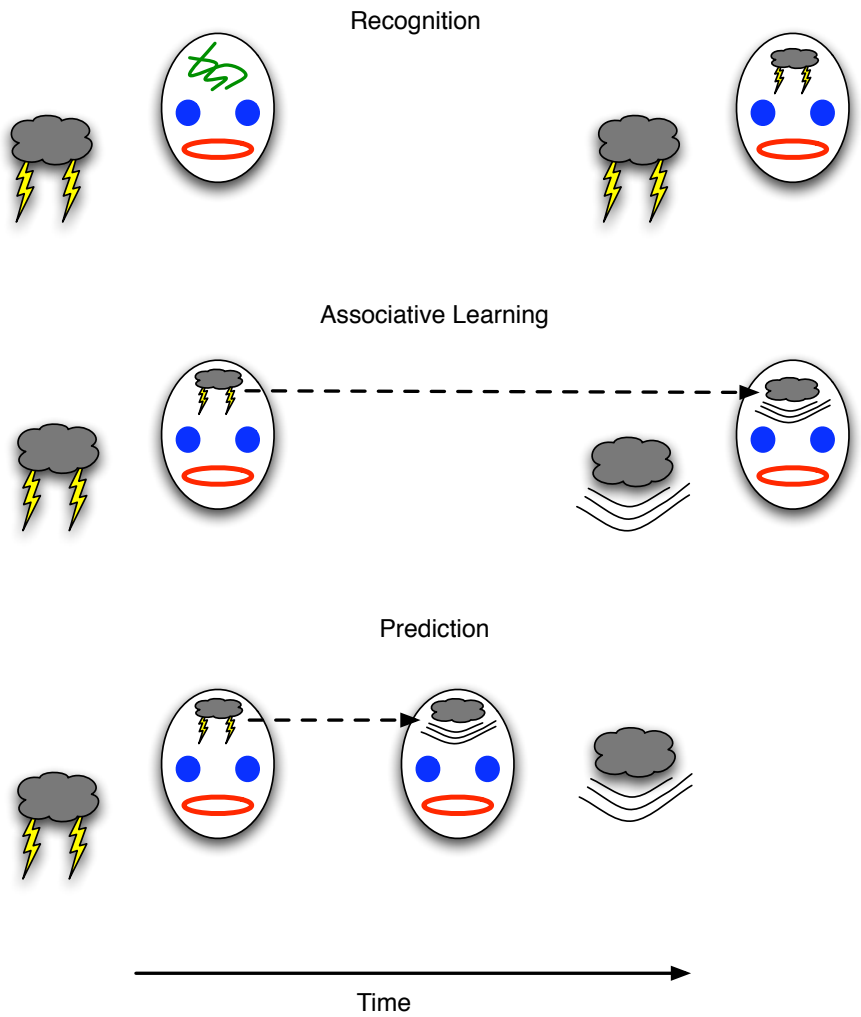
To make known formally, officially, or **explicitly**

Indicate

- To point out or point to
- To be a **sign**, symptom or **index** of

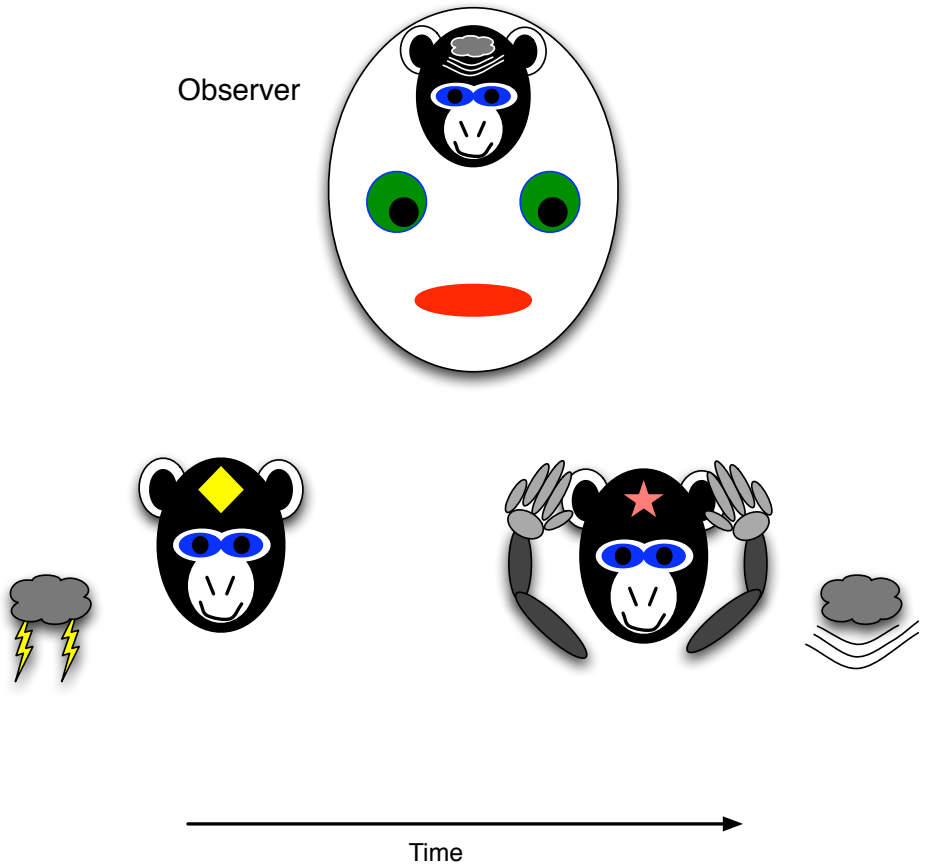
...Webster's Online Dictionary

Declarative Prediction



Procedural Prediction

To an observer, the agent's actions **indicate** knowledge of a future world state.



Eye Tracking Simulations

Kettner, Mahamud, Leung, Sitkoff, Houk, Peterson and Barto (1997)

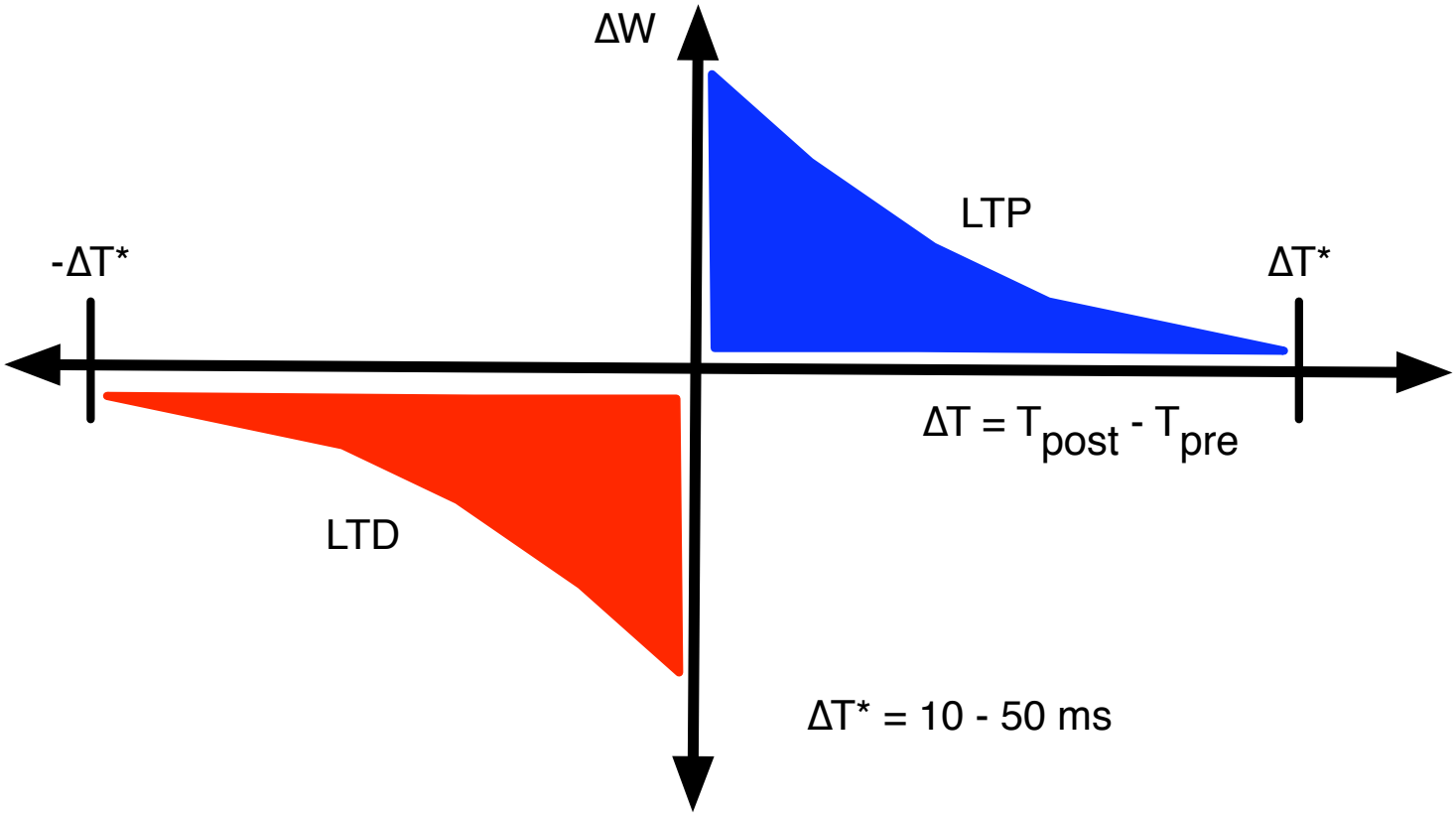
> *This tracking behavior is considered **predictive** because visual signals are processed by the smooth pursuit system with considerable delays ($\approx$ 100 ms)...One would expect tracking to lag by similar delays if the eye were controlled exclusively by a simple negative feedback system based on visual input...(pg. 2115)*

Procedurally Predictive

To an observer, it may appear that the controller has an **explicit representation** of the ball's future location, but actually it just knows how to **move the eye** to point there.

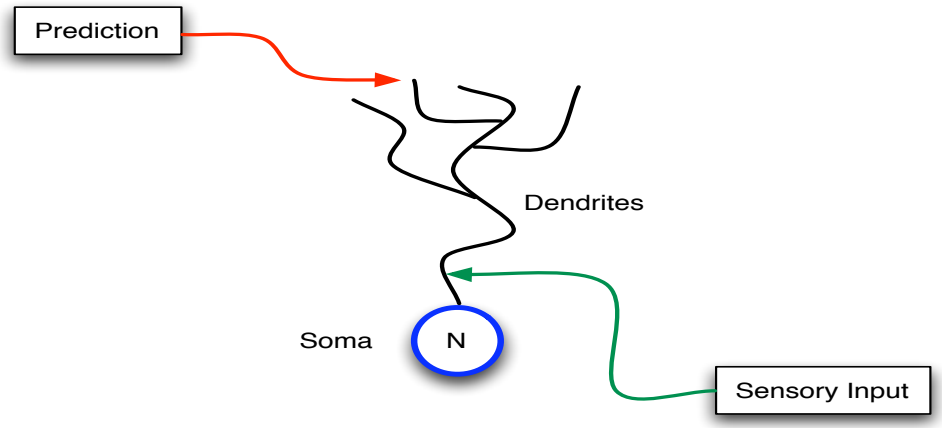
Spike-Timing Dependent Plasticity (STDP)

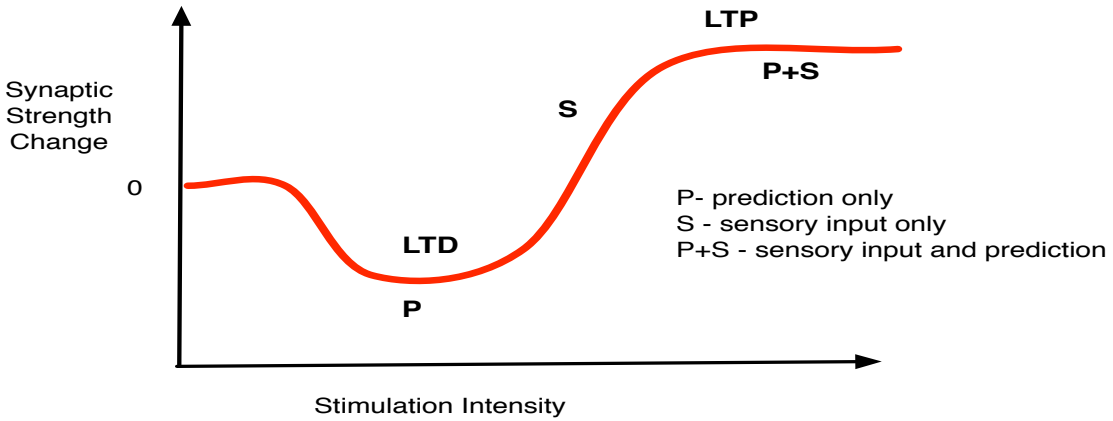
Markram et. al. (1997), Bi et. al. (1998)



Bi-Modal Thresholding

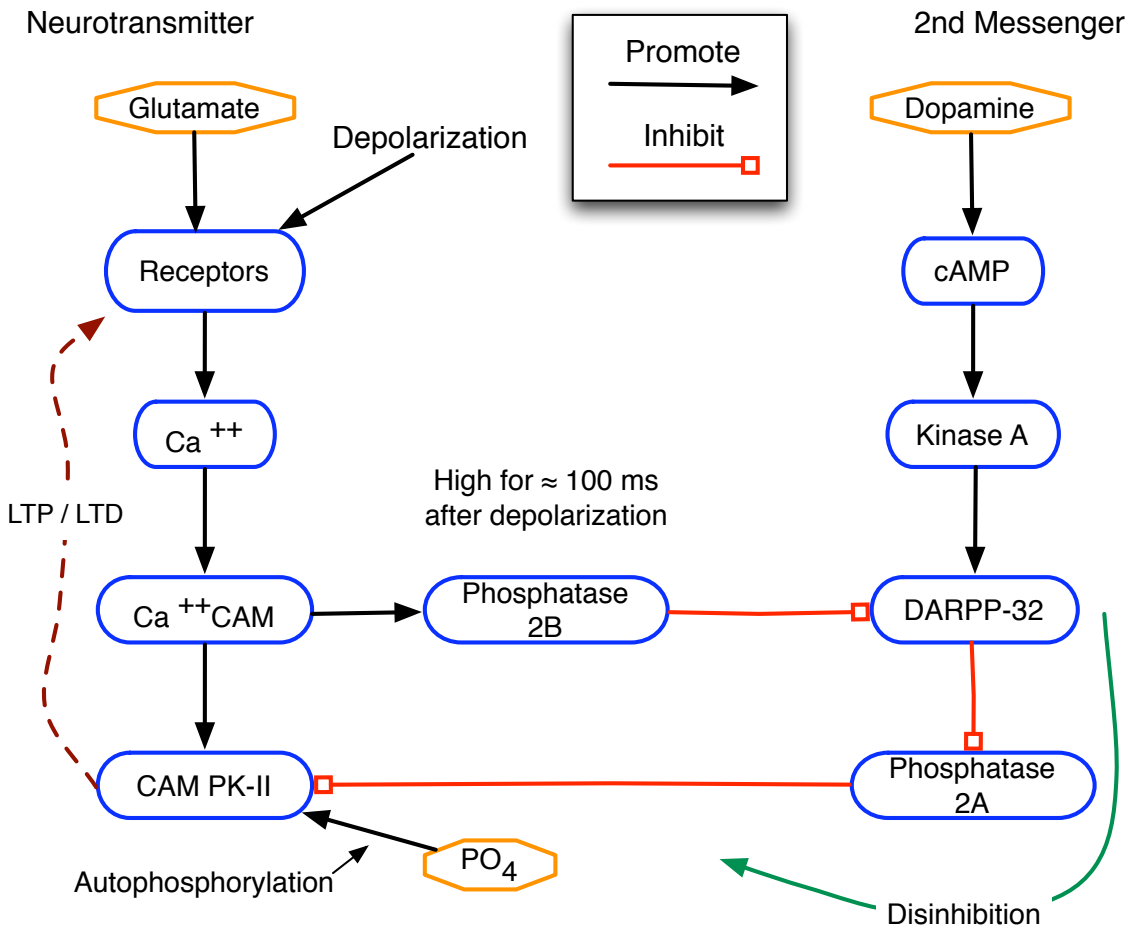
Artola, Brocher and Singer (1990)



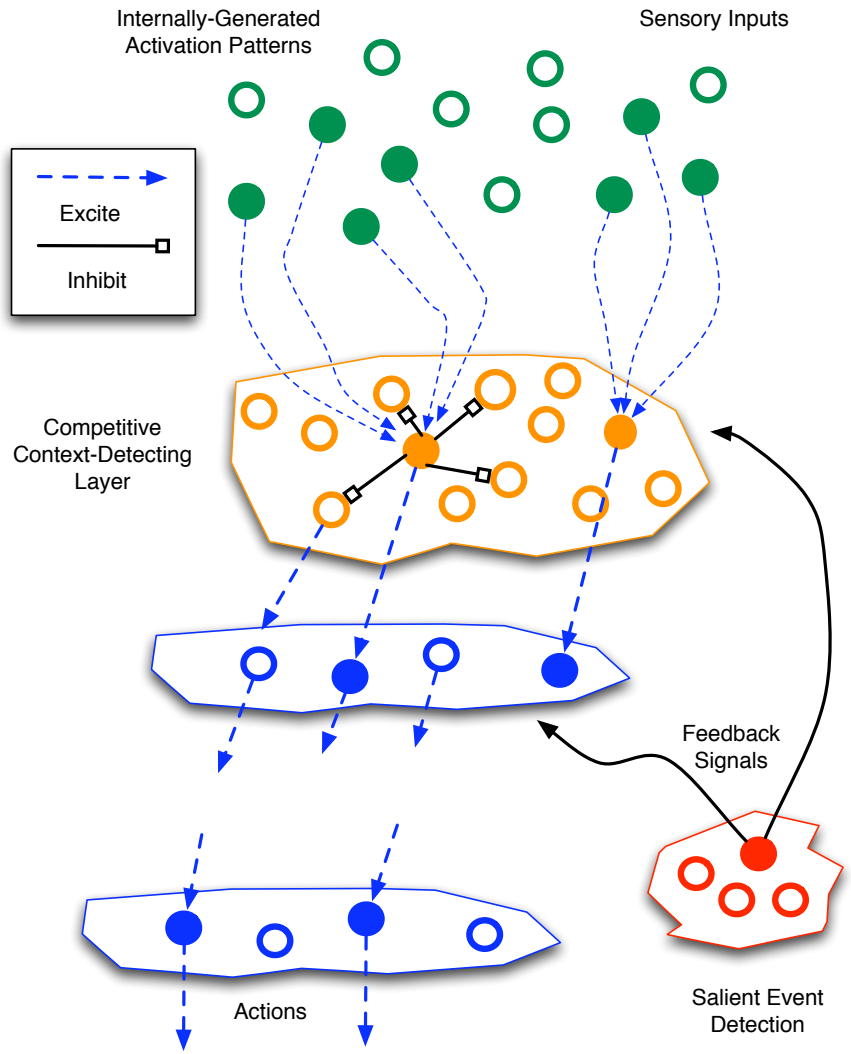


Chemistry of Eligibility Traces

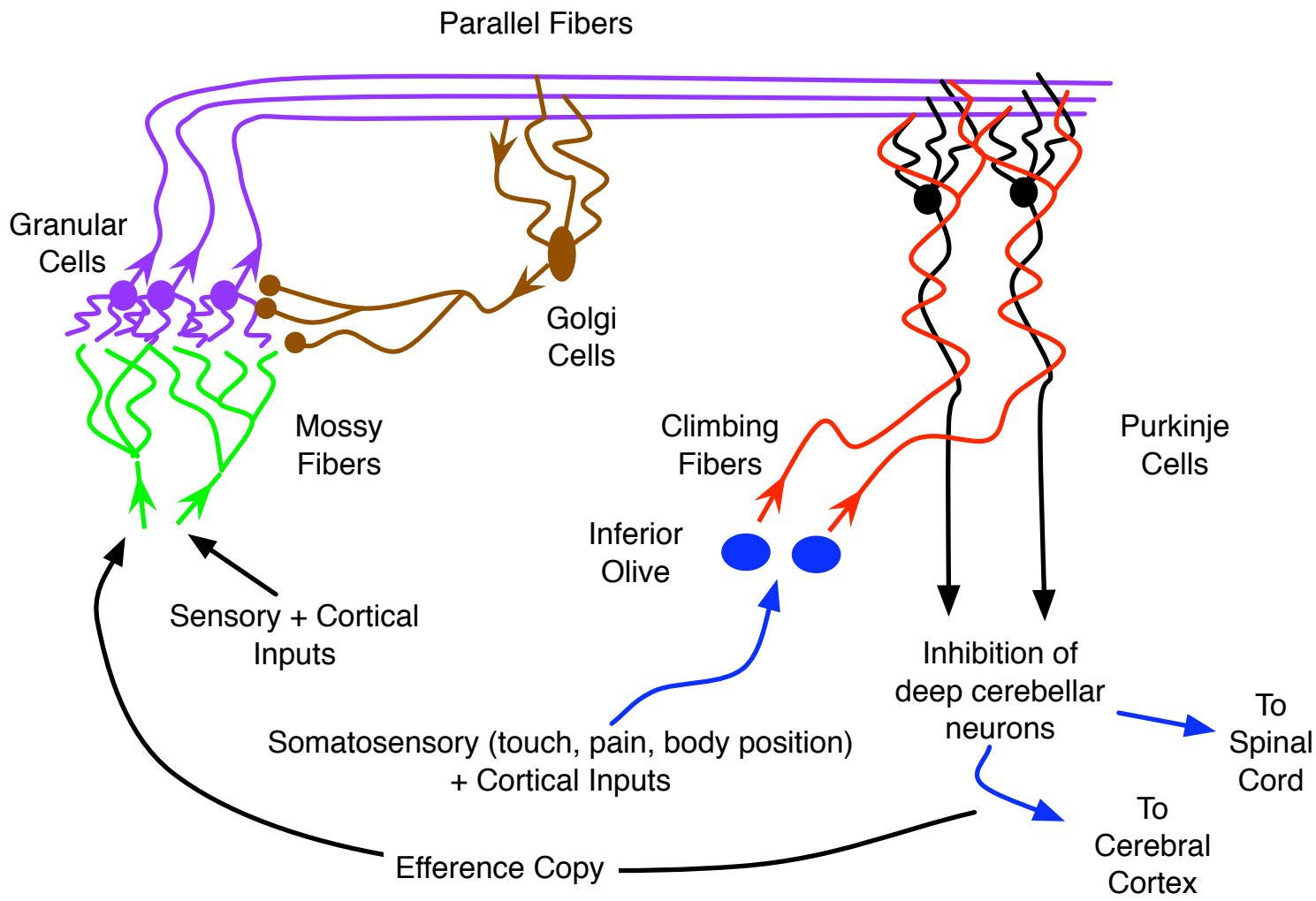
Houk, Adams and Barto (1998)



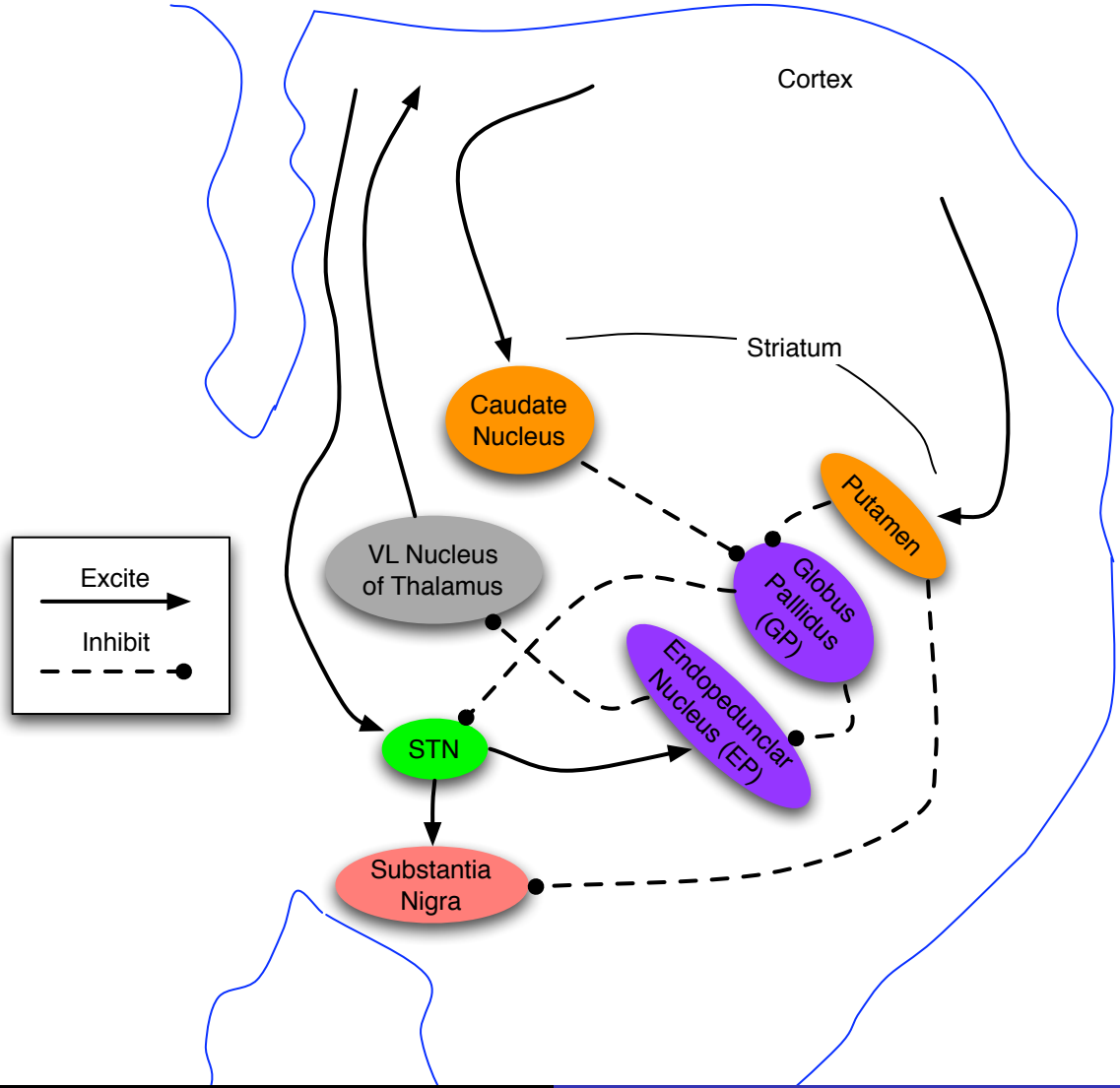
Generic Procedural Prediction Network



The Cerebellum

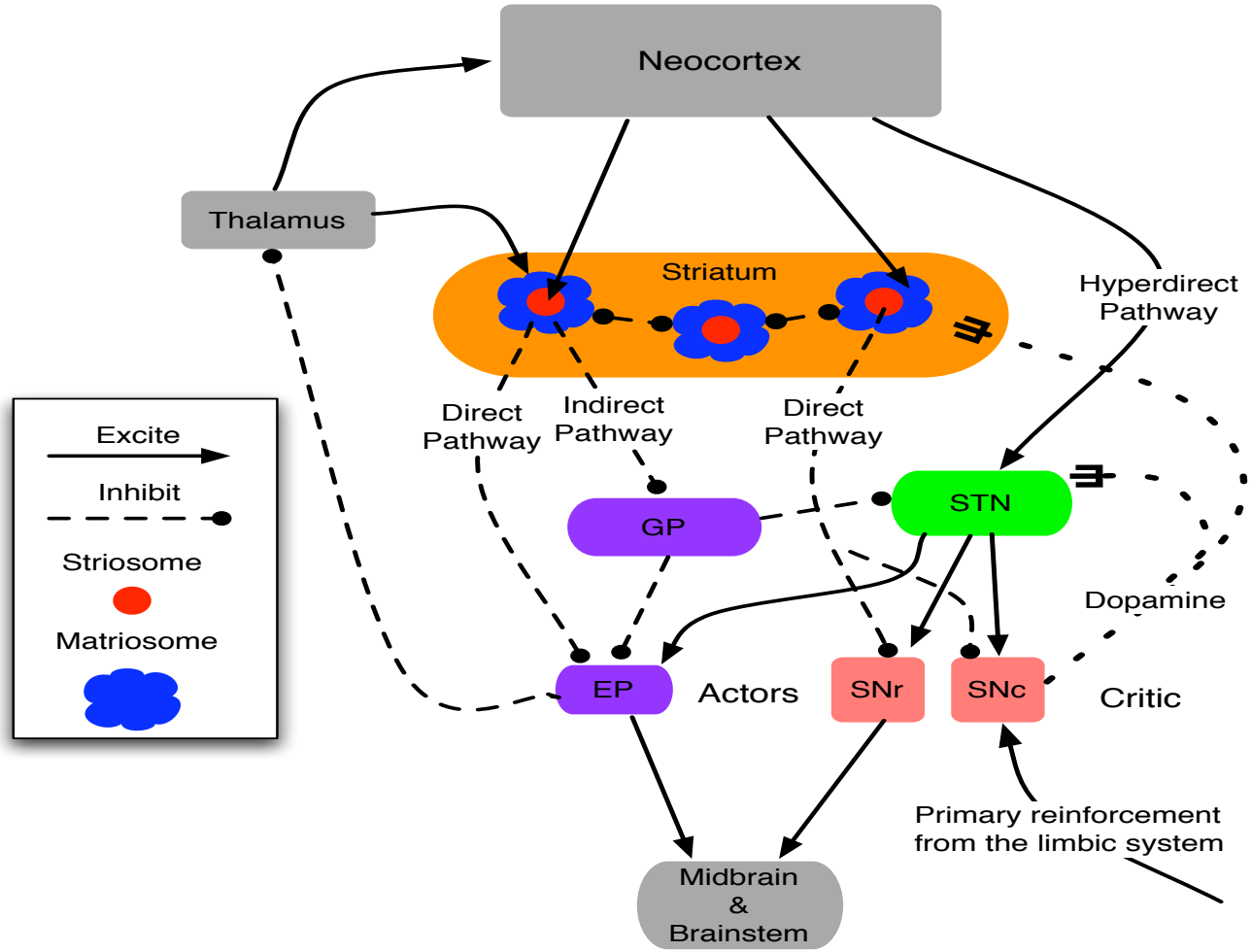


Basal Ganglia: Anatomy

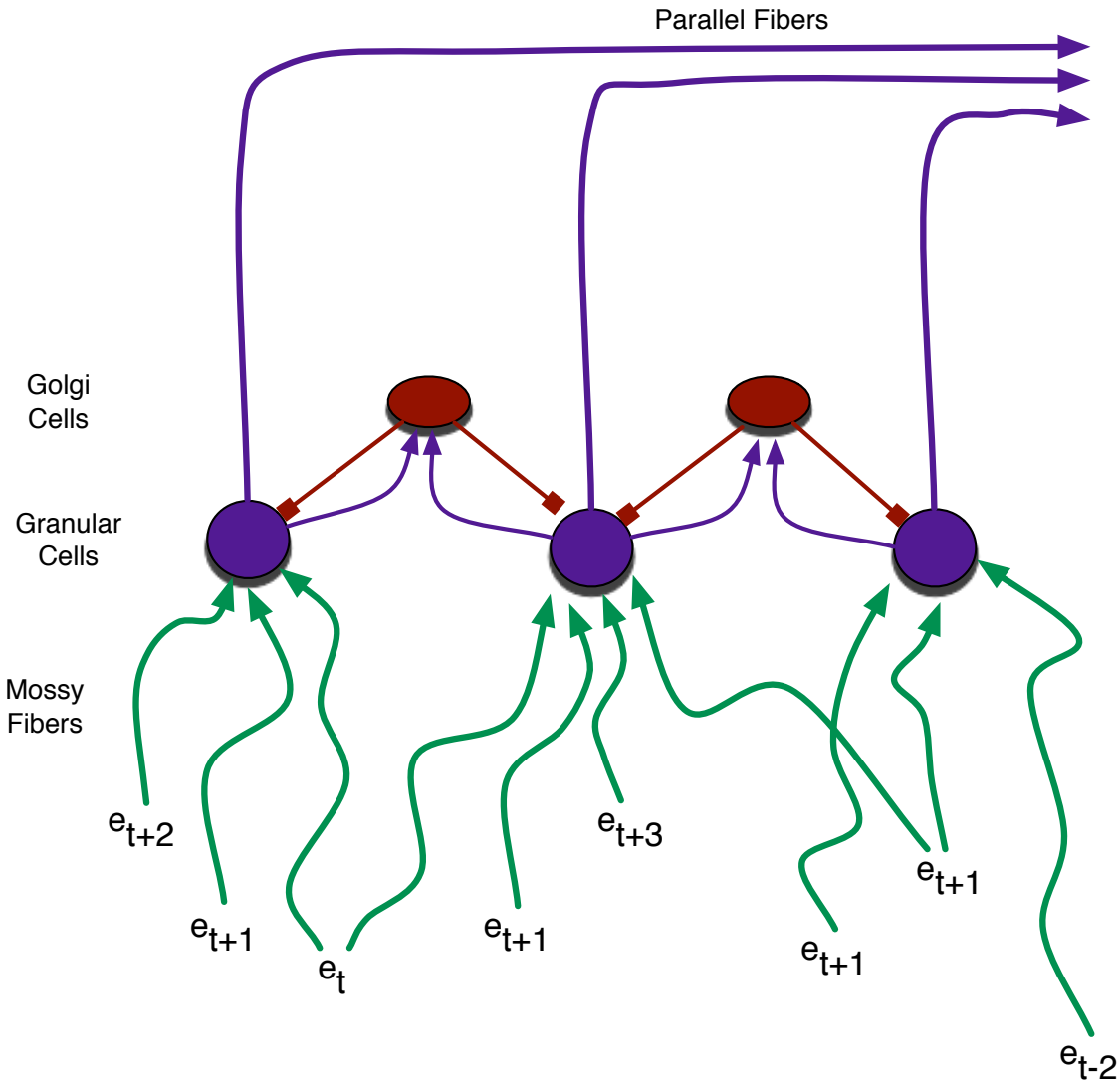


Basal Ganglia: Function

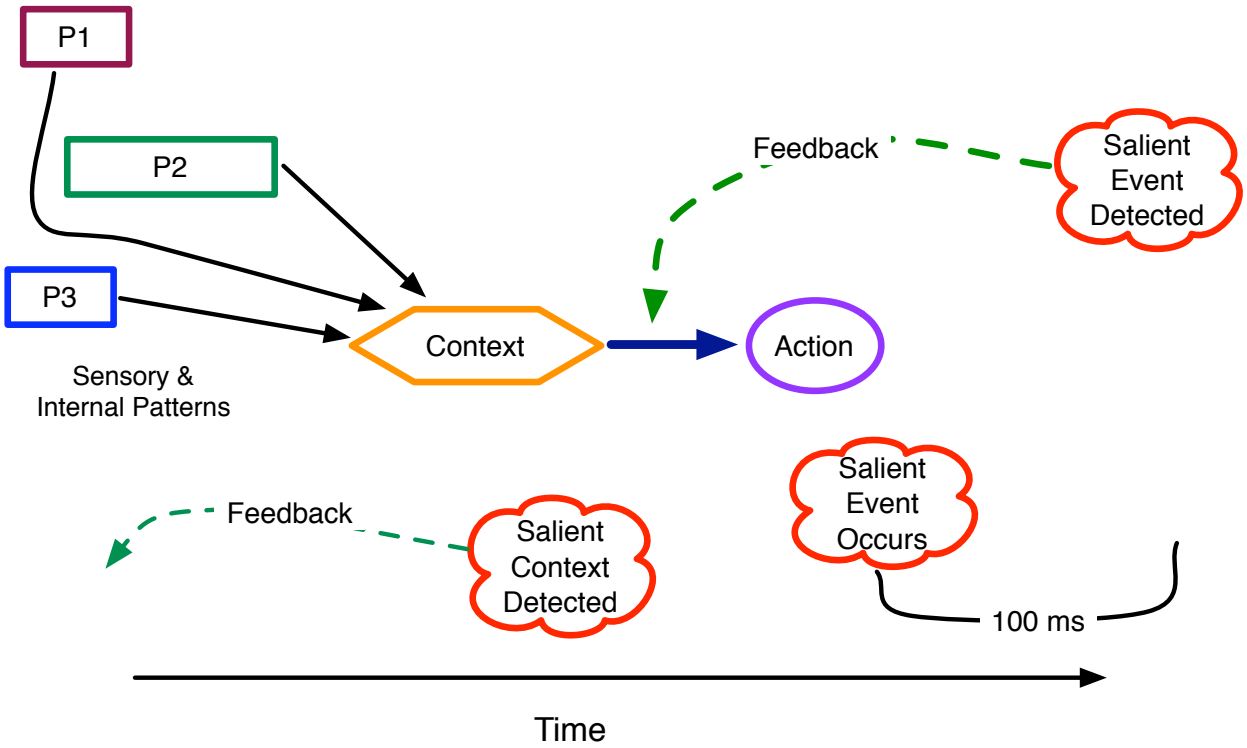
Houk, Davis and Beiser (1998). *Models of Info Proc in the BG*



Mixed-Temporal Context Coding



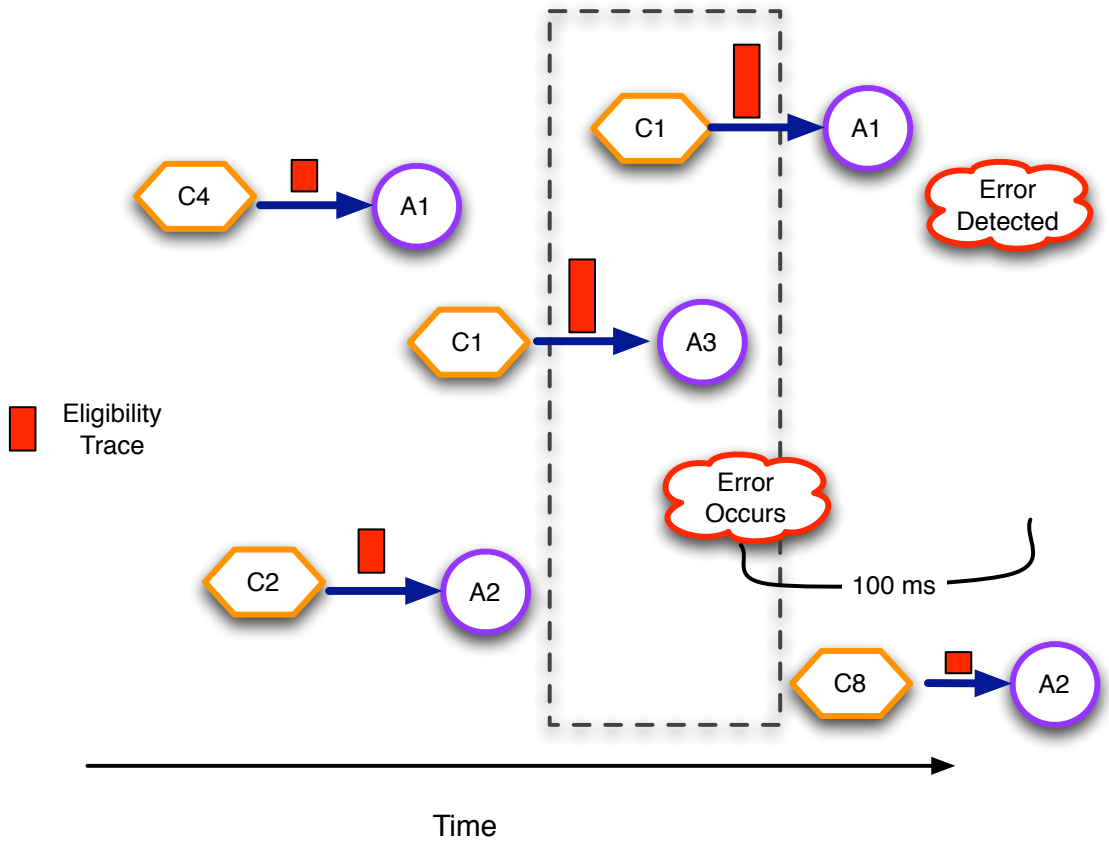
Predictive Learning in Procedural Networks



At time T, and given situation at $T - \delta_1$ compute the best action for $T + \delta_2$

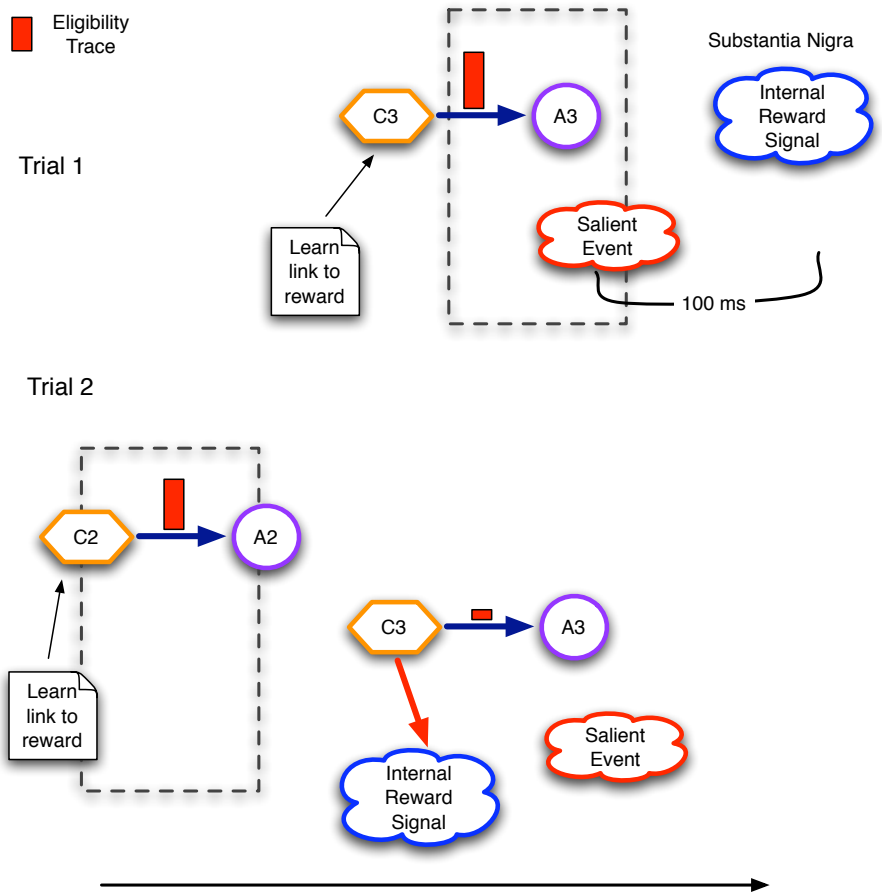
Eligibility Traces in the Cerebellum

LTD: Those PF-PC synapses active $\approx$ 100 ms before error detection ($\approx$ when error occured) are $\Downarrow$ most.

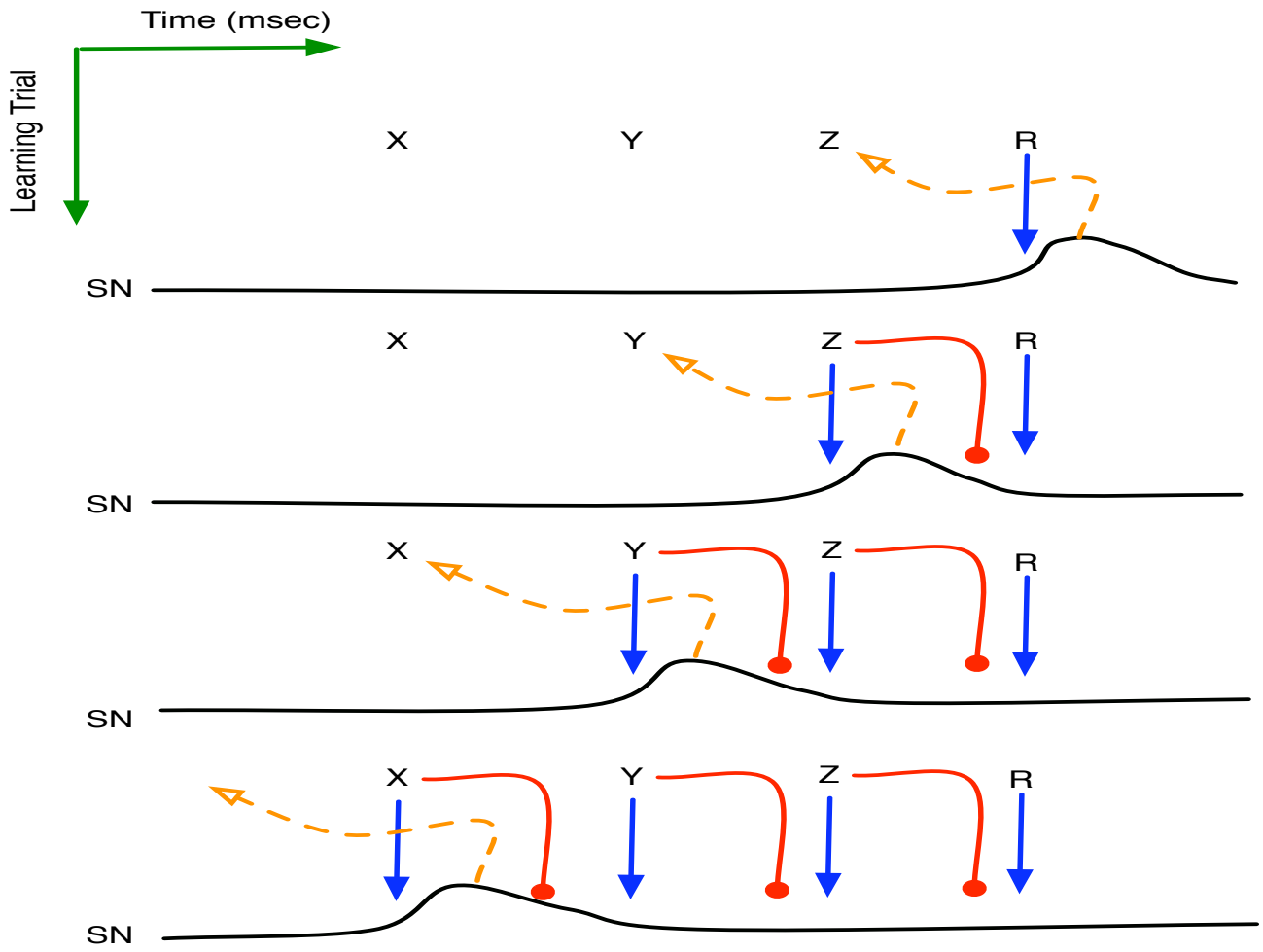


Eligibility Traces in the Basal Ganglia

LTP: Corticostriatal and striatal-pallidal synapses that are active 100 ms before t_{reward} ($\approx t_{salient\ event}$) are $\Uparrow$ most.

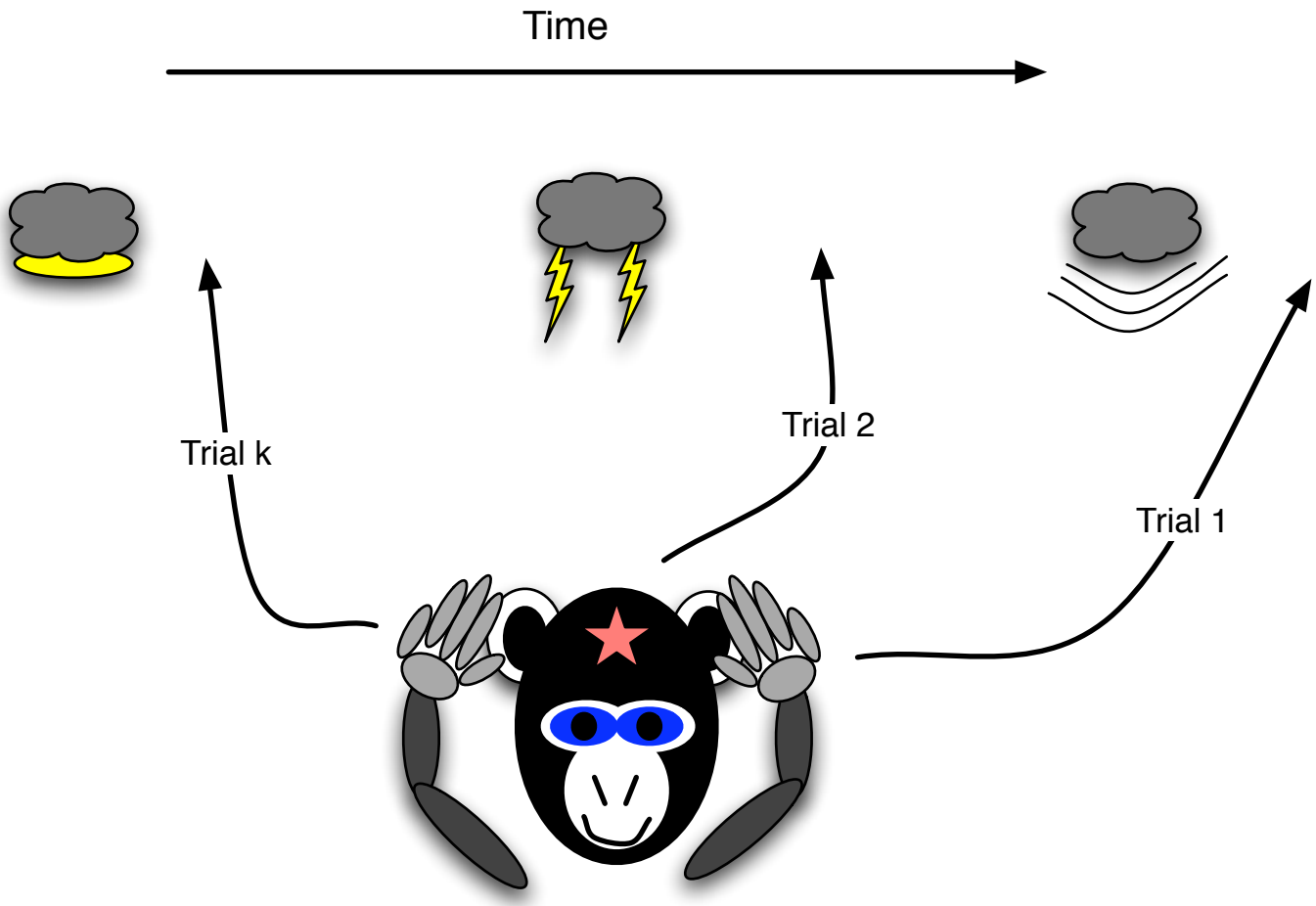


Reinforcement Learning in the Basal Ganglia



Regressive Procedural Prediction

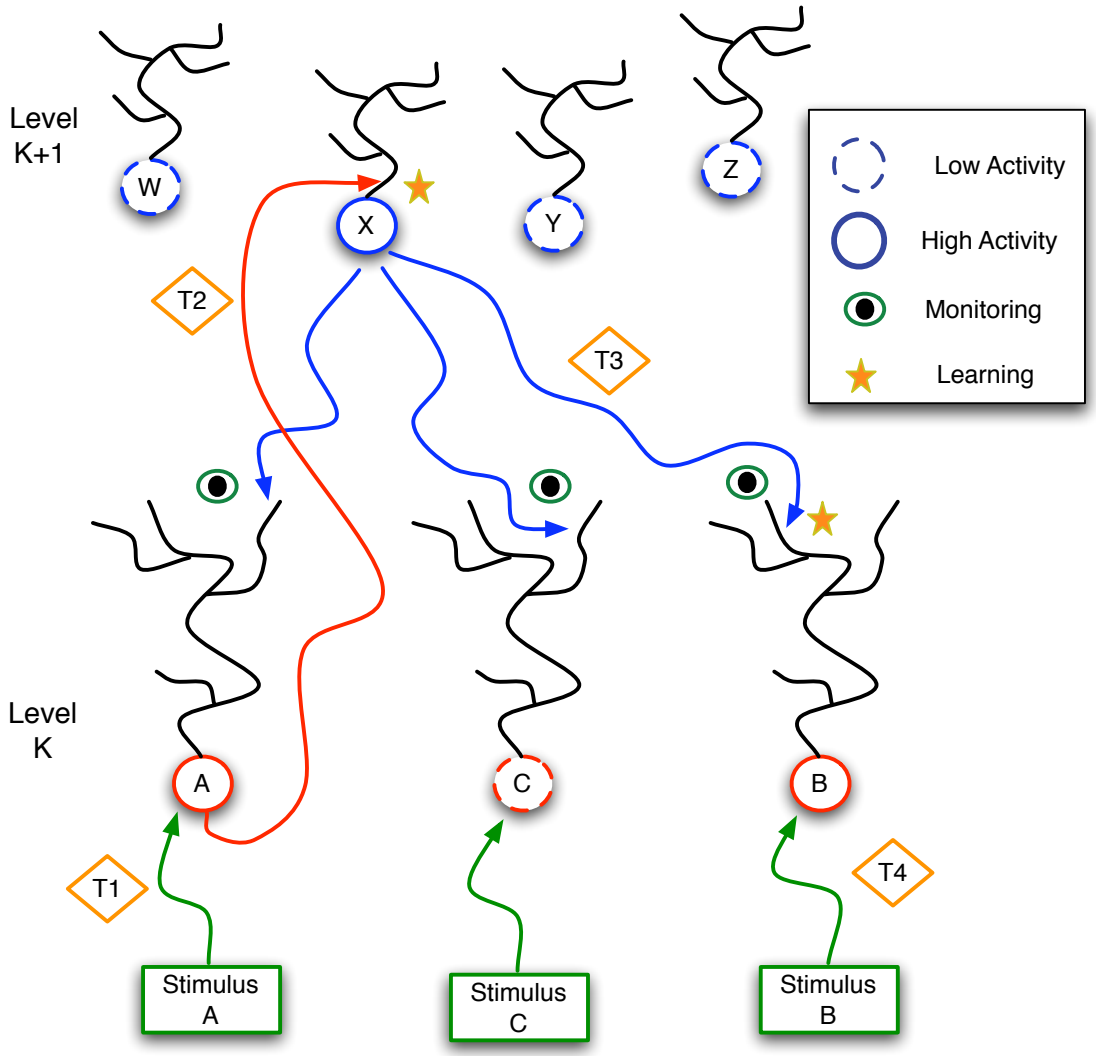
Displaying predictive behavior at progressively earlier times.



Procedural Prediction in CB and BG

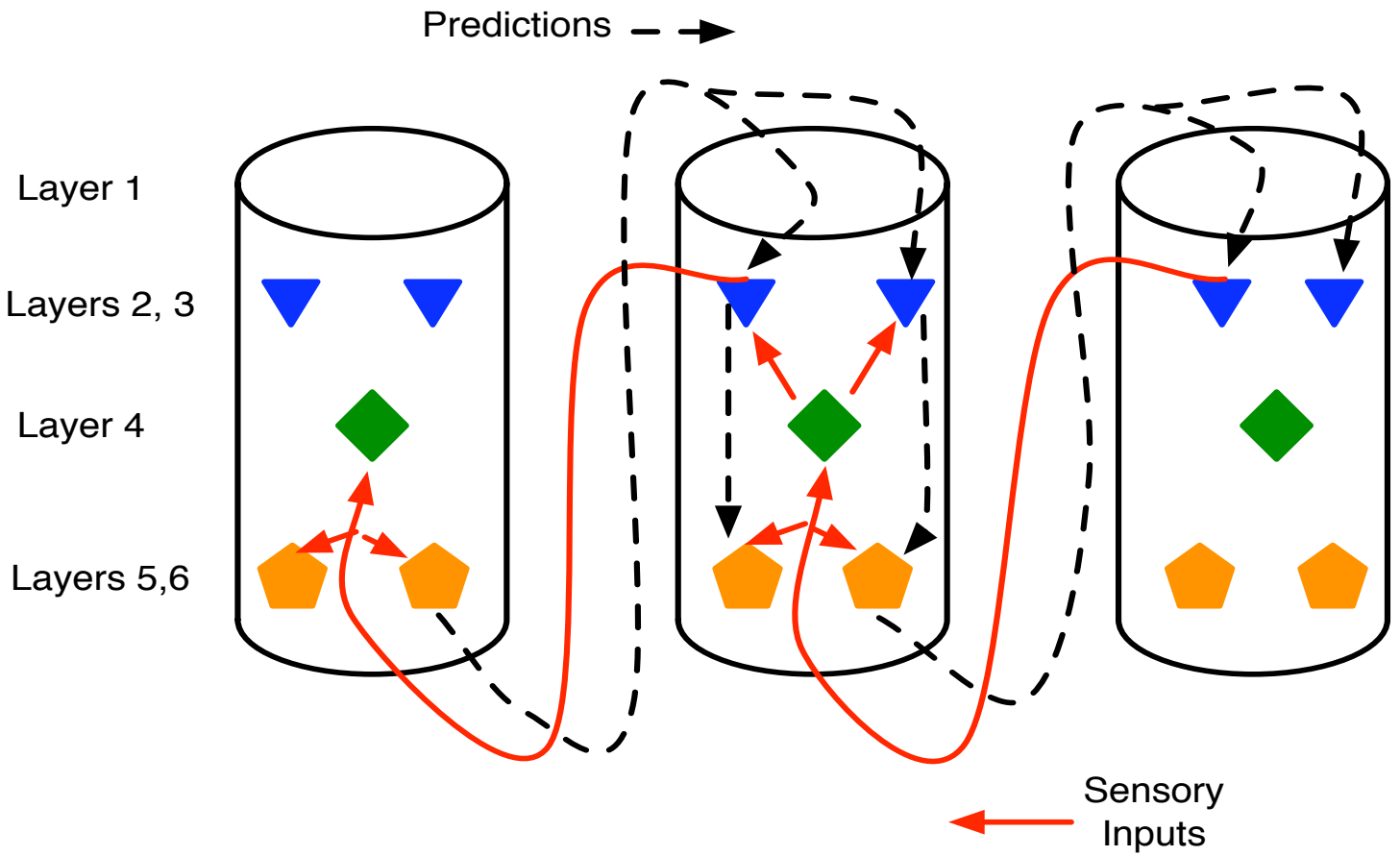
1. Neural architectures and dynamics that adapt (over evolutionary and lifetime) timescales to inherent delays in sensory processing and motor activation.
2. Implicit predictive knowledge in context-action circuitry:
   - Choose appropriate actions for time $T + \delta_2$ based on state of the world at $T - \delta_1$.
   - Learn to indicate future situations well before they occur.

Generic Declarative Prediction Network

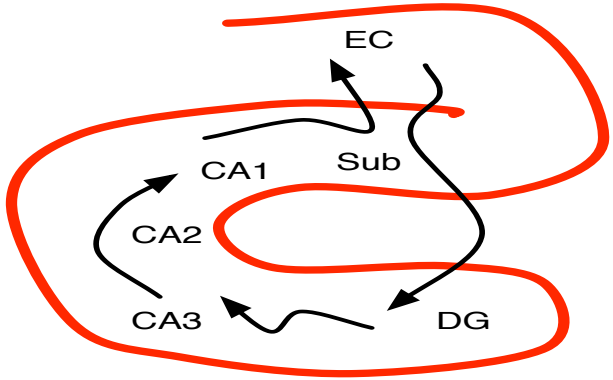


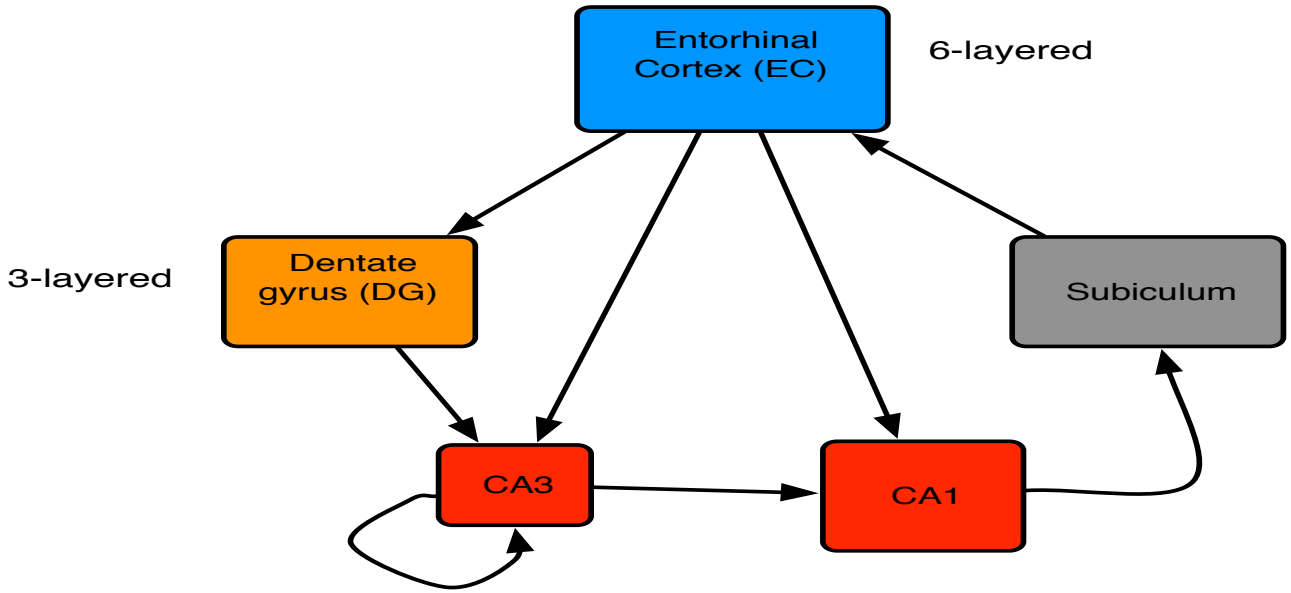
Cortical Columns

Hawkins (2004), *On Intelligence*

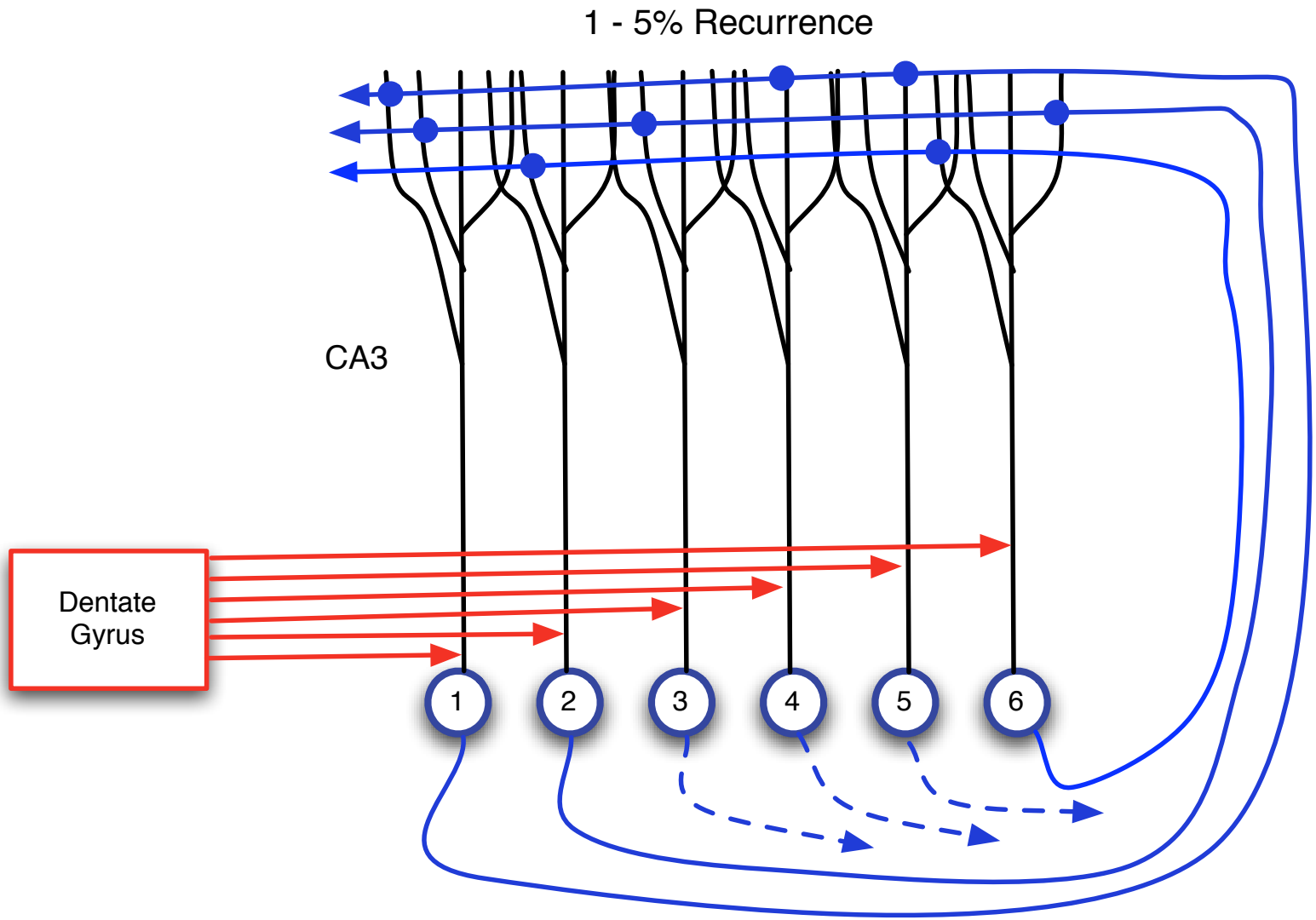


Hippocampus: Anatomy



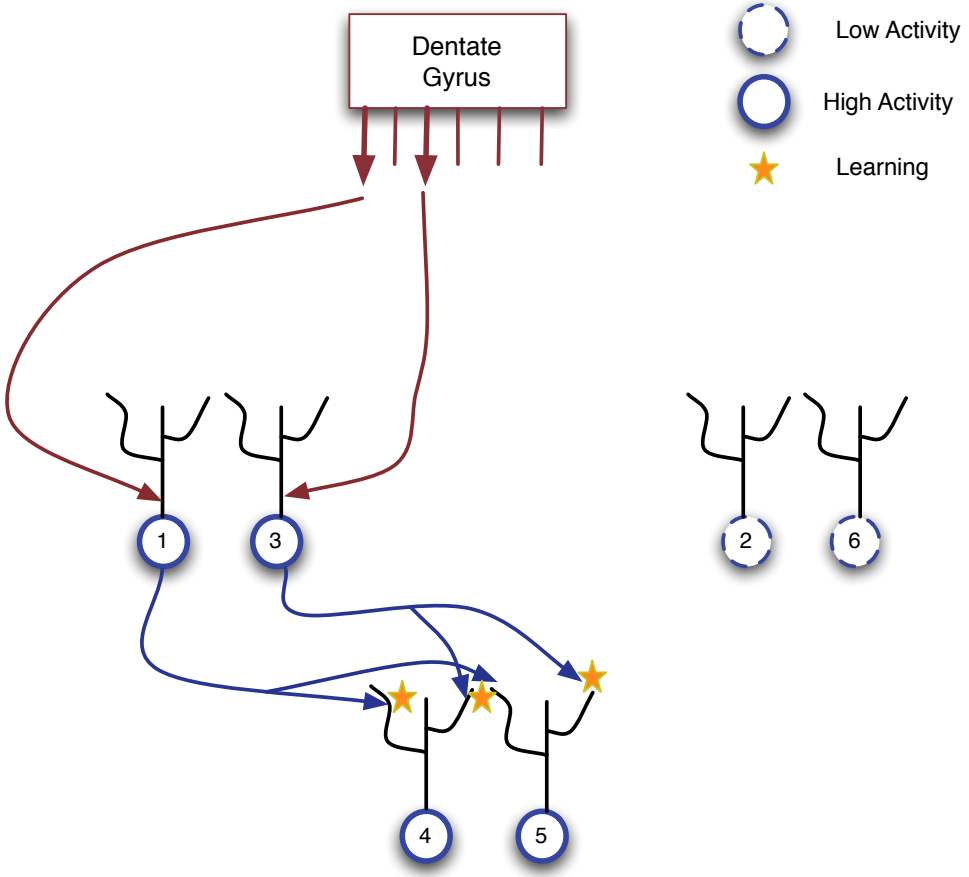


Recurrent Topology

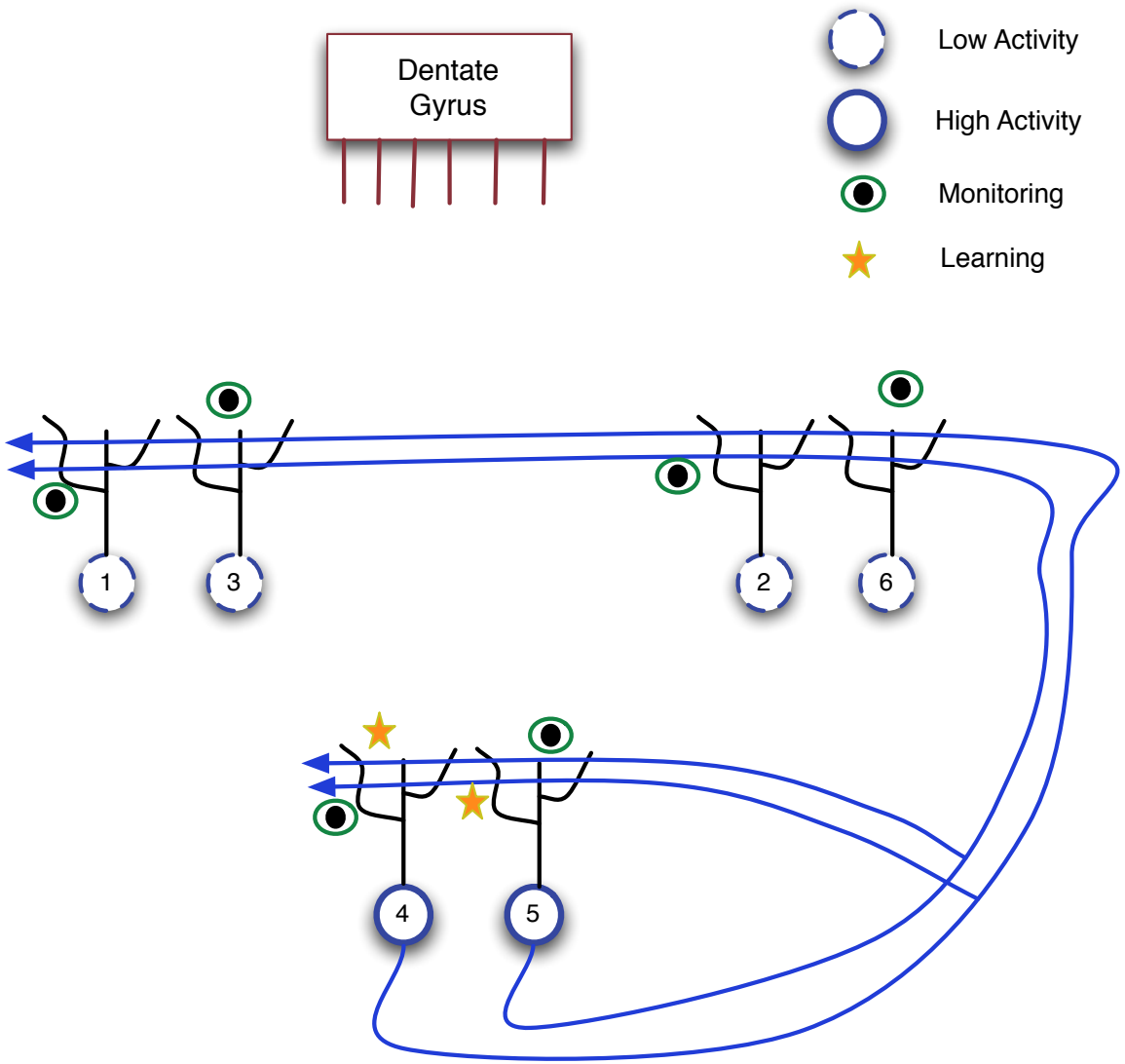


First Input and Context Formation

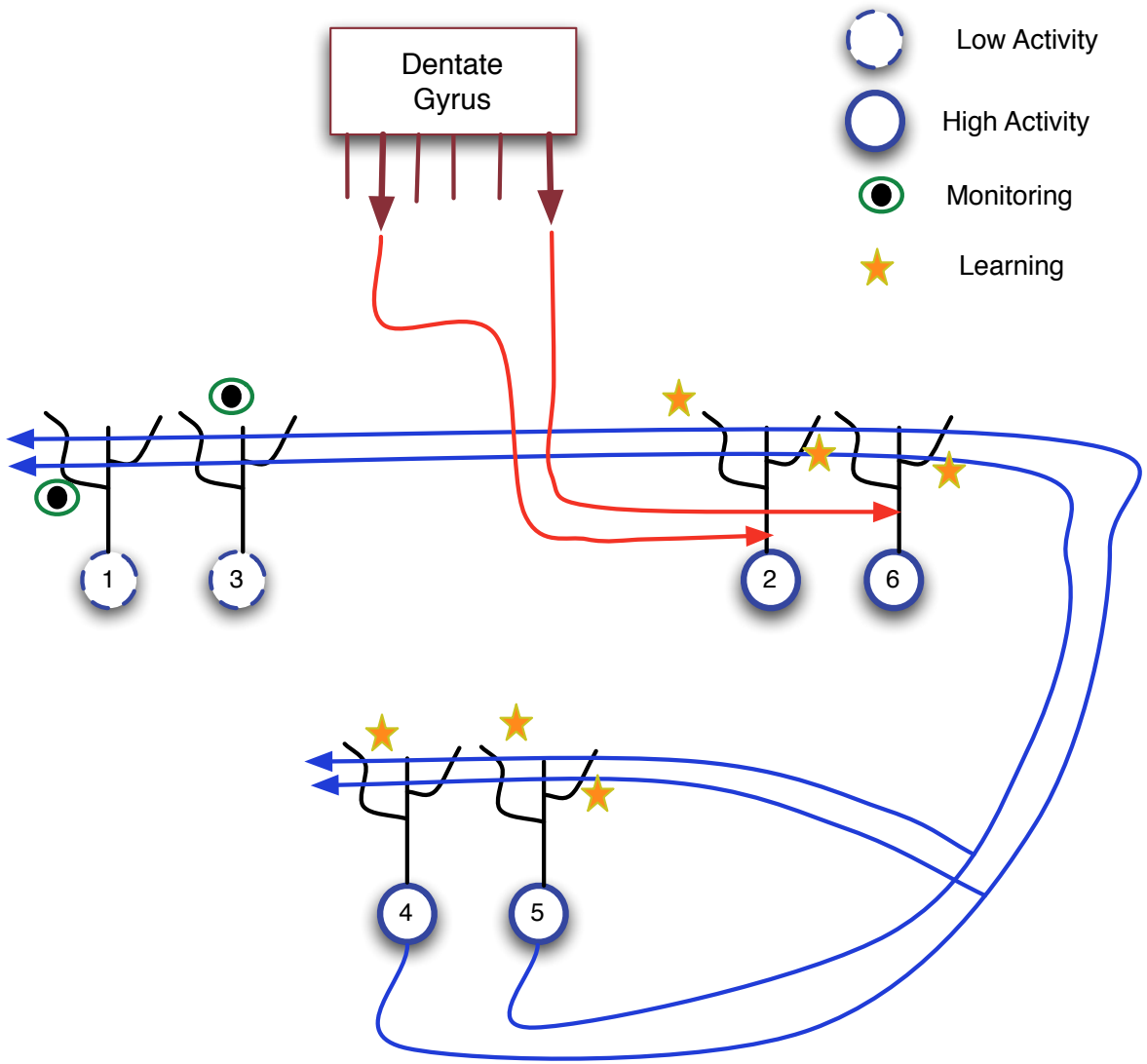
Wallenstein, Eichenbaum and Hasselmo(1998)



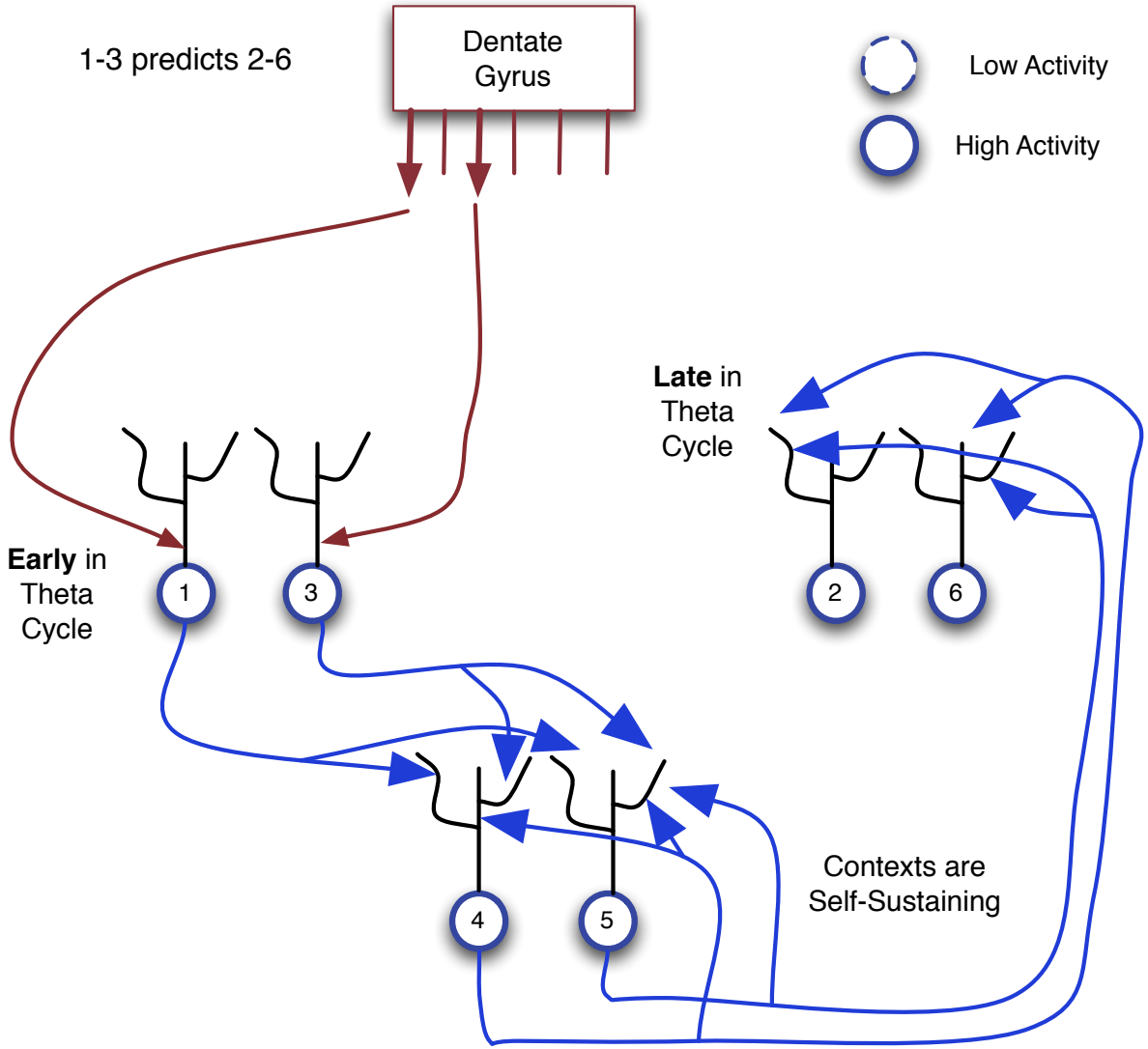
Monitoring by Context Neurons



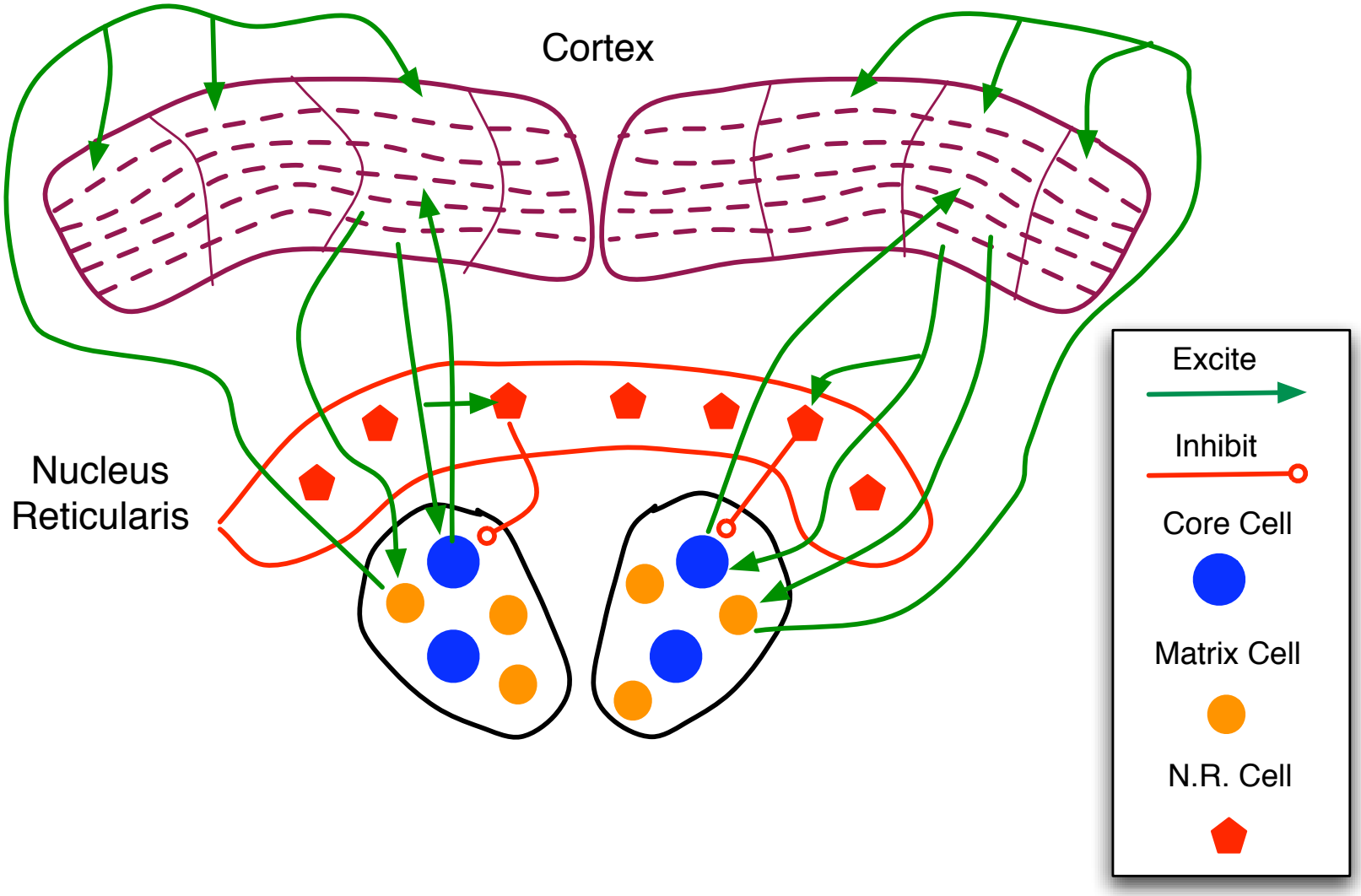
Second Input and Linkage to Context



Using the New Prediction

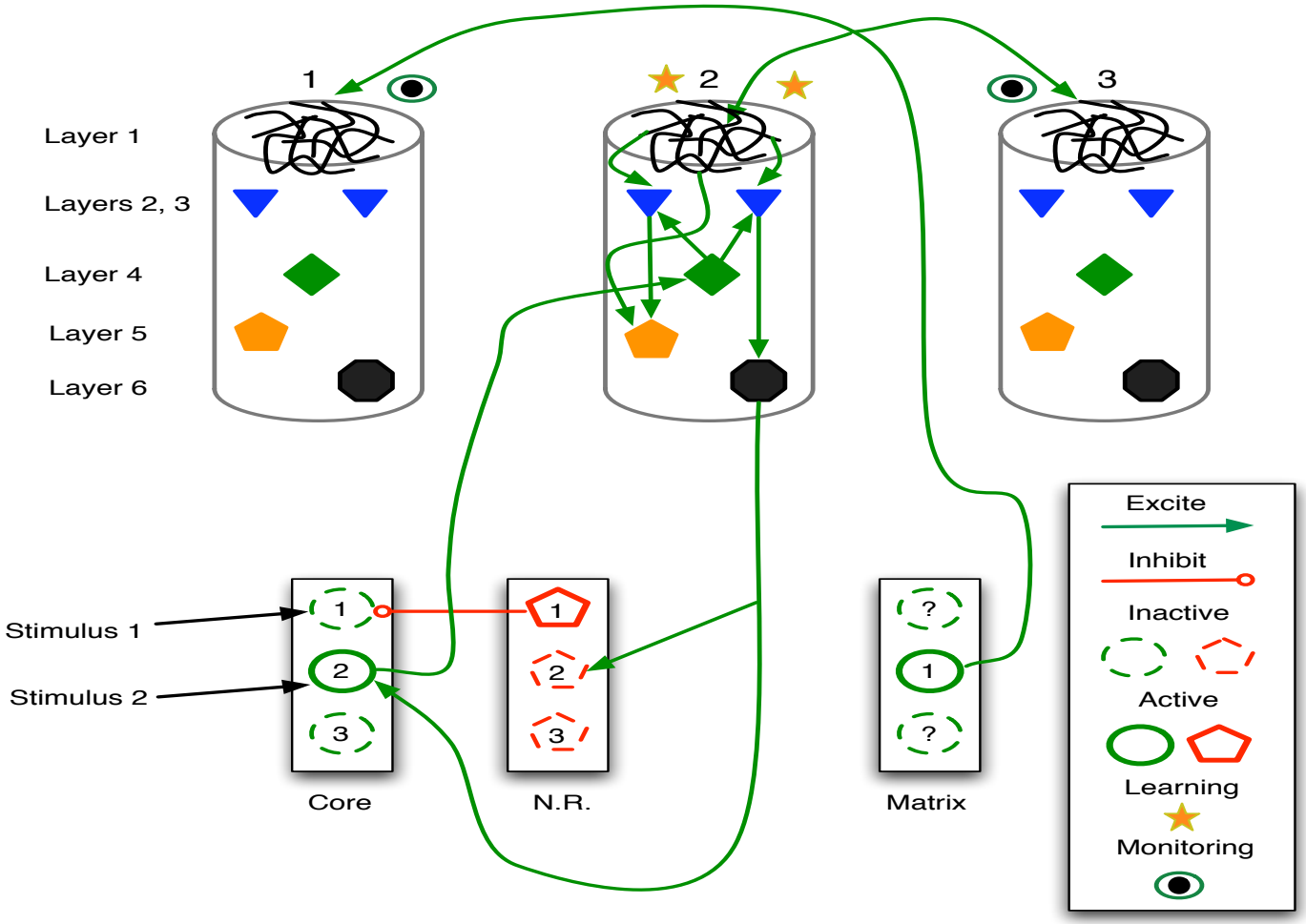


Thalamacortical System: Anatomy



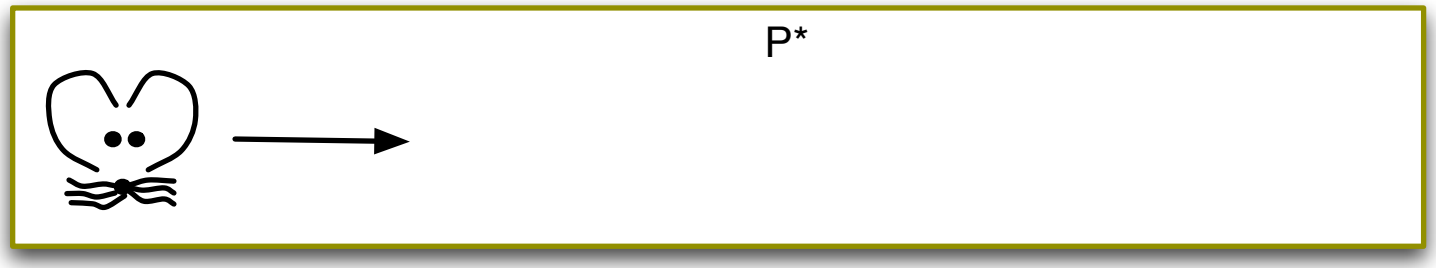
Incremental Sensory Processing via GDPN

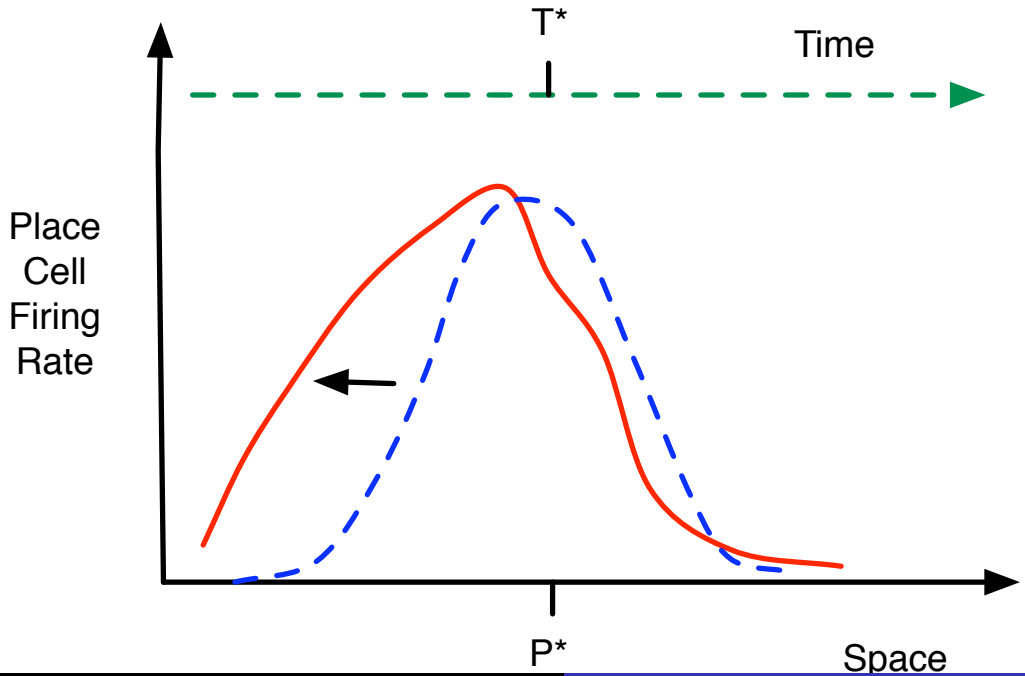
Rodriguez, Whitson and Granger(2004)



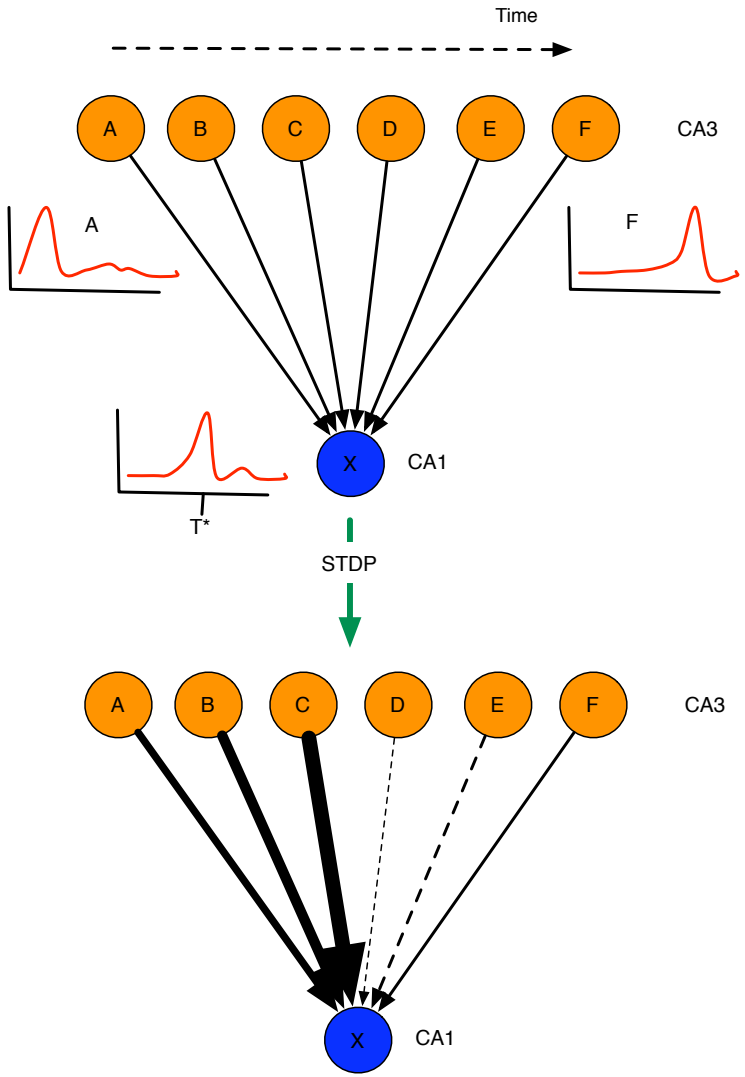
Asymmetric Place Cells

Neural Dynamics of Predictive Coding. Mehta, 2001

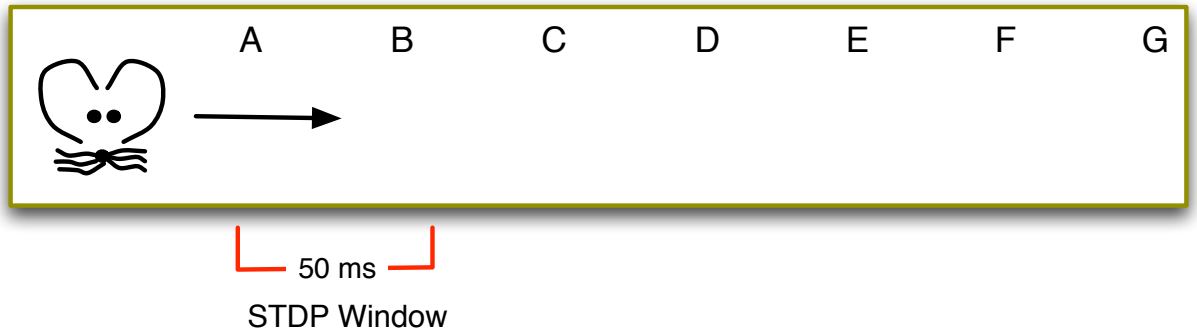




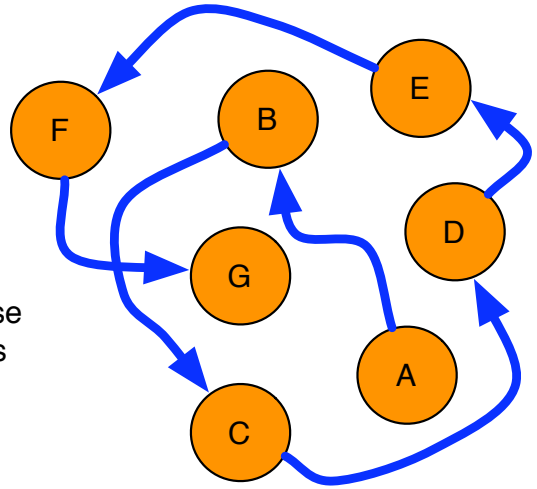
STDP → Asymmetry → Predictive Coding



Place Cell Linkage → Prediction



STDP can produce these connections

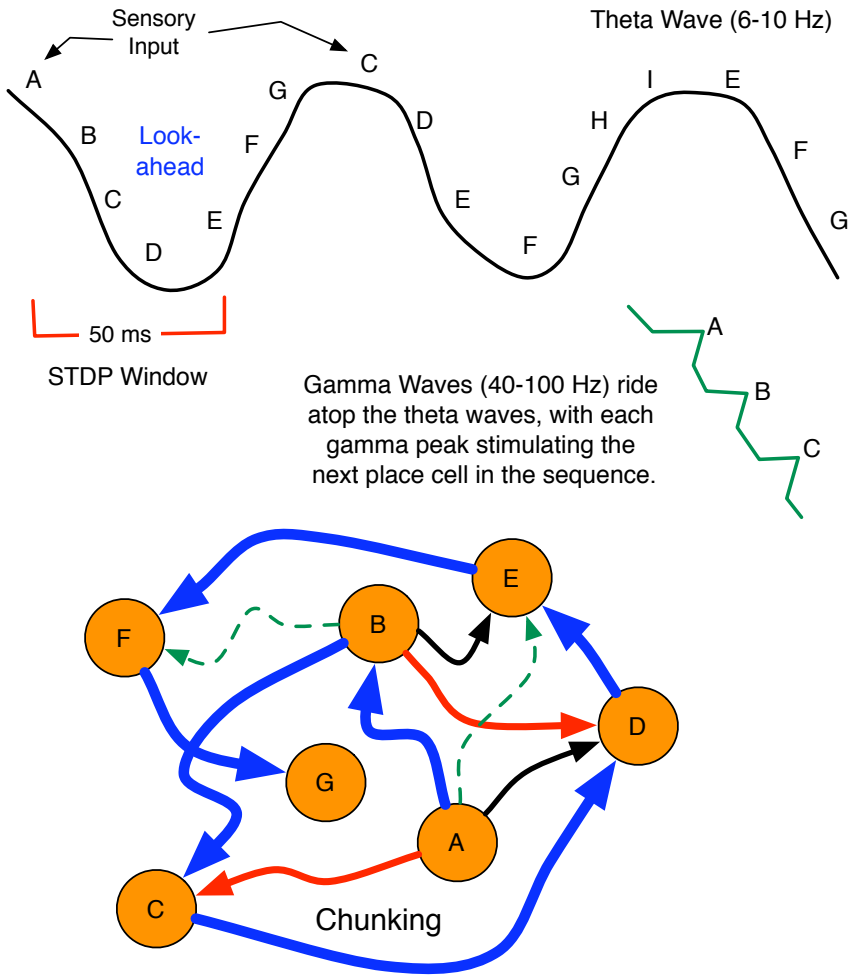


CA3
Place Cells

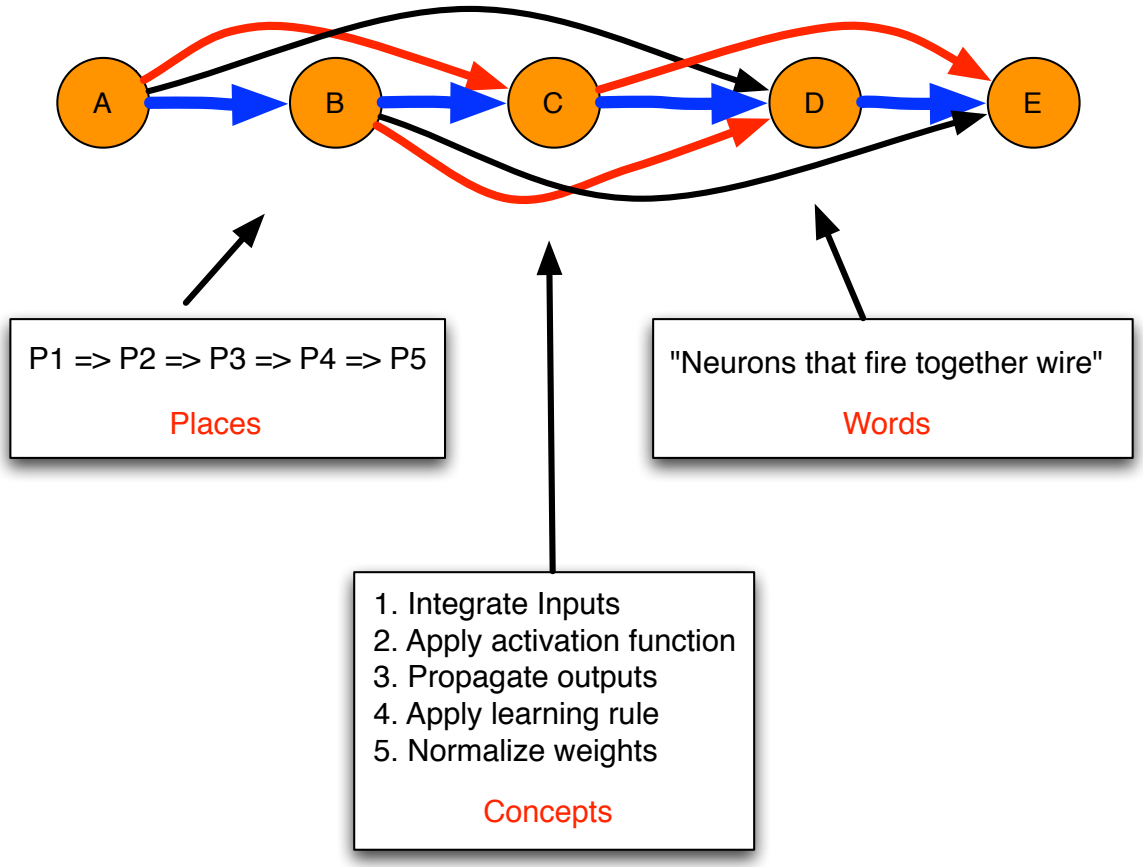
- Random recurrence (2-5%)
- No topology

Theta Phase Precession → Prediction Chunks

Prediction, sequences and the hippocampus. Lisman & Redish, 2009



Generality of Place Cells and Chunking



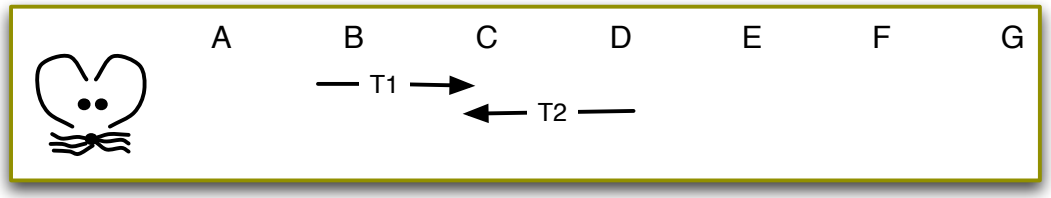
Place cells and theta phase precession useful for linking any declarative sequences (episodes).

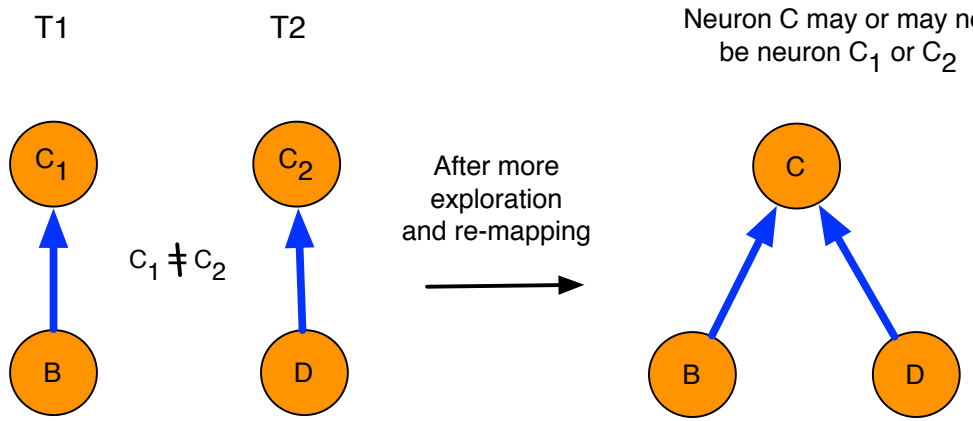
Episodes to Concepts

Rhythms of the Brain. Buzsaki, 2006.

- Place cells are unidirectional in corridors but omnidirectional in open arenas.
- They generalize after exploration and path crossings.
- Similarly, a set of overlapping episodes can generalize to a concept.
- Concept = essence of episodes, minus (a lot of detailed) spatiotemporal context.
- What is the neural basis for this type of generalization?
  - Place-Cell Remapping (*Place representation within hippocampal networks is modified by LTP*. Dragoi, Harris & Buzsaki, 2003)
  - Biased synaptic potentiation and/or stability

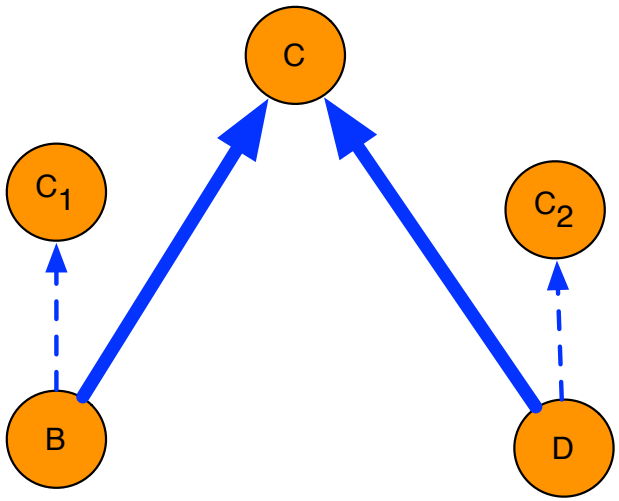
Place Cell Generalization



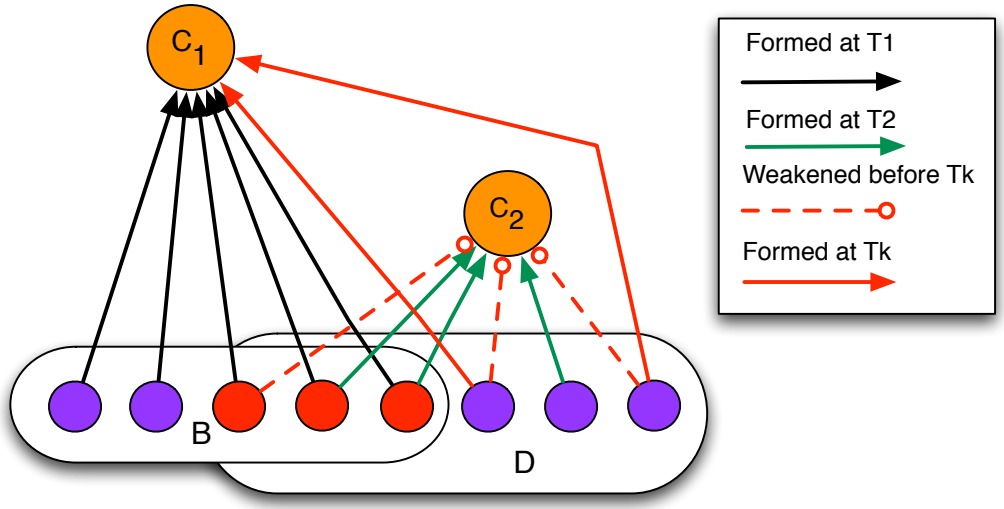


Episodes to Concepts: Possible Neural Mechanisms

Disjuncts Favored



Biased Re-mapping



1. Broader (disjunctive) context more stable, since it is active more often.
2. B-D cue overlap makes C_1 most likely target for D if some $D \rightarrow C_2$ synapses weaken.

Innate Hippocampal Predictive Mechanisms

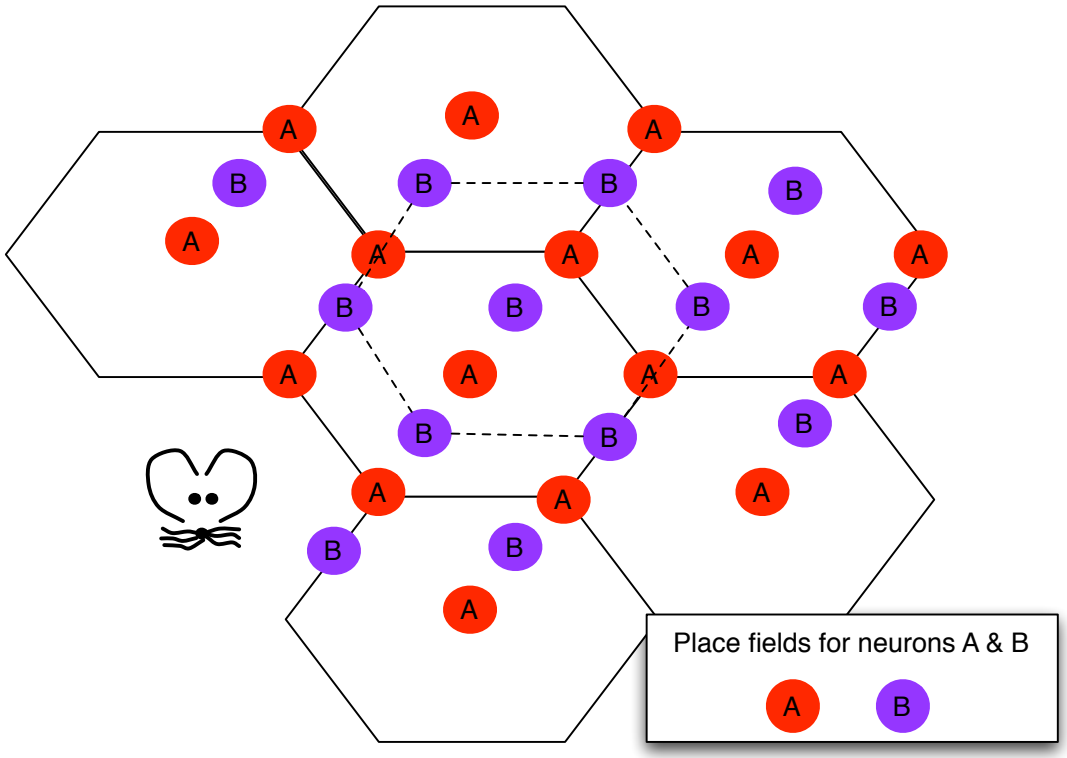
- *New experiences enhance coordinated neural activity in the hippocampus*. Cheng & Frank, Neuron, 2008.
- Some phase precession seen in **novel** environments. How?

Grid Cells

- *Microstructure of a spatial map in the entorhinal cortex*. Hafting et. al., Nature, 2005.
- *Hippocampus-independent phase precession in entorhinal grid cells*. Hafting et. al., Nature, 2008.

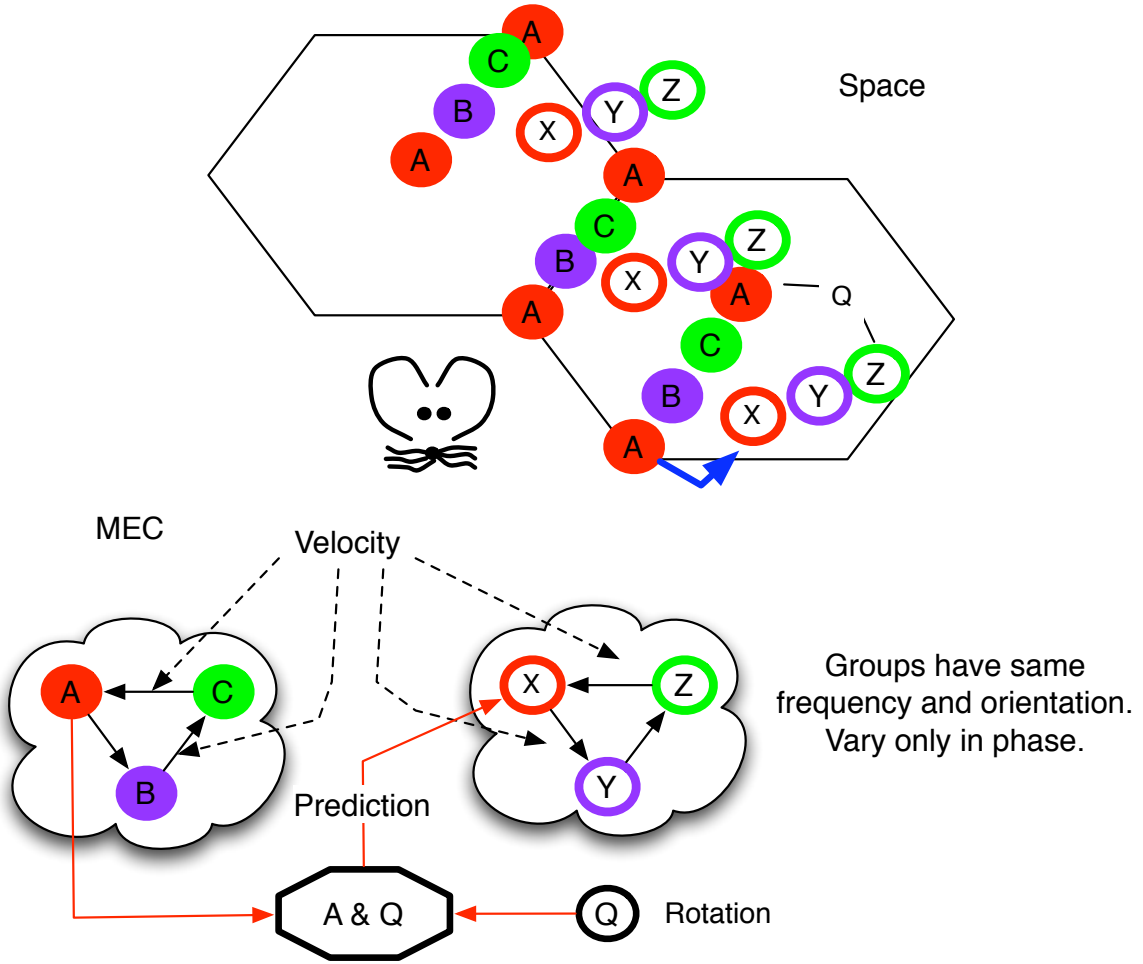
Grid Cells

- Medial Entorhinal Cortex (MEC) Layers II & III
- Mainly layer II shows theta precession, but II and III could support theta-based prediction in CA3.

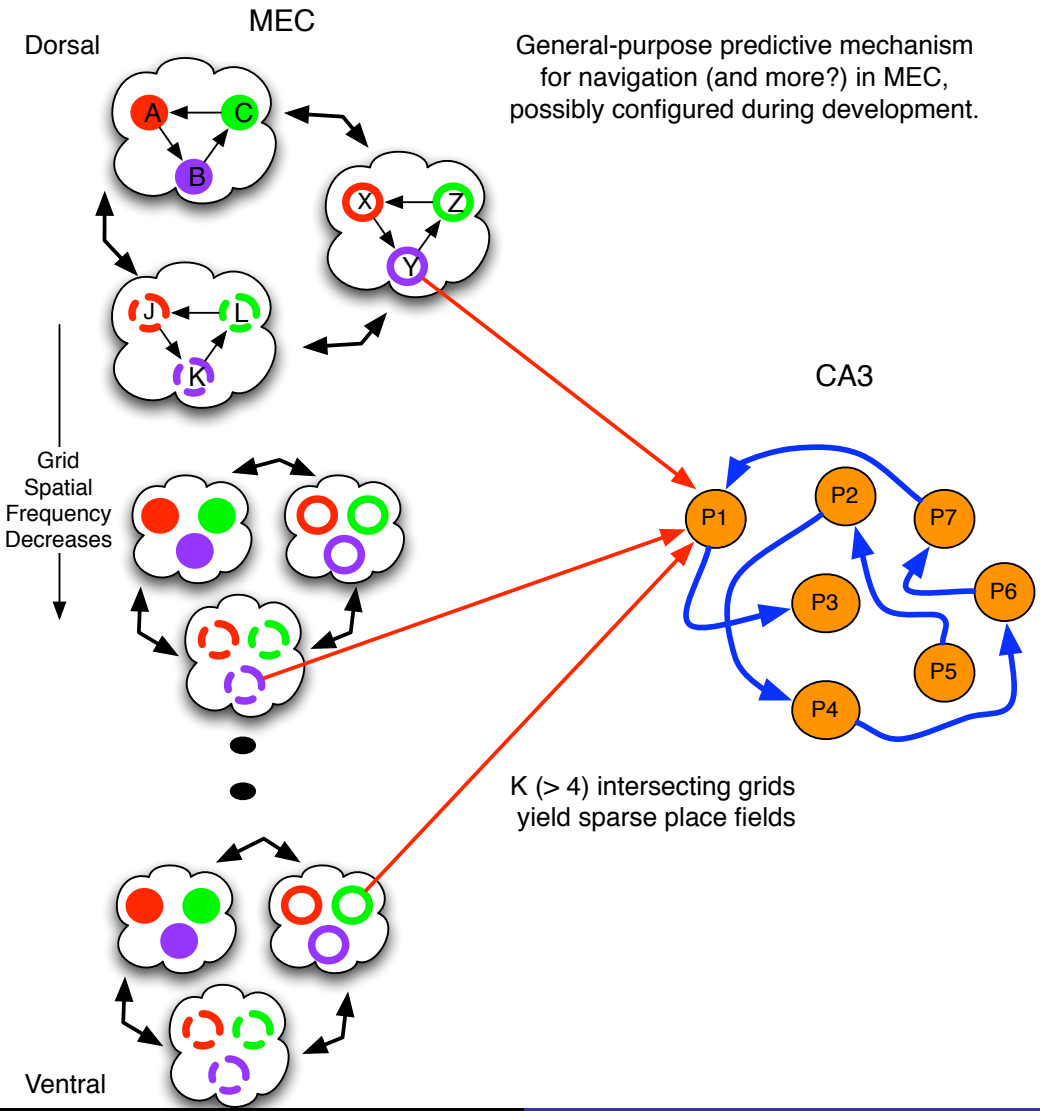


Proposed Grid-Cell Circuitry

McNaughton et. al., 2006

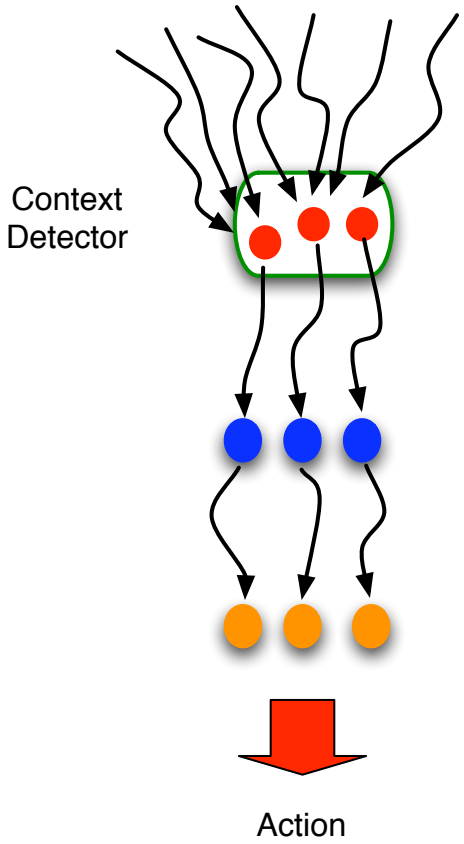


MEC Grid Cells ⇒ CA3 Place Cells

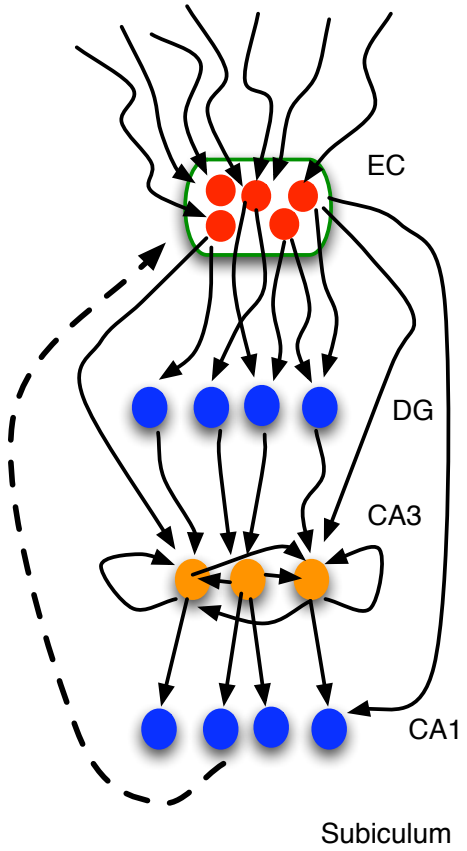


Comparative Anatomy for Prediction

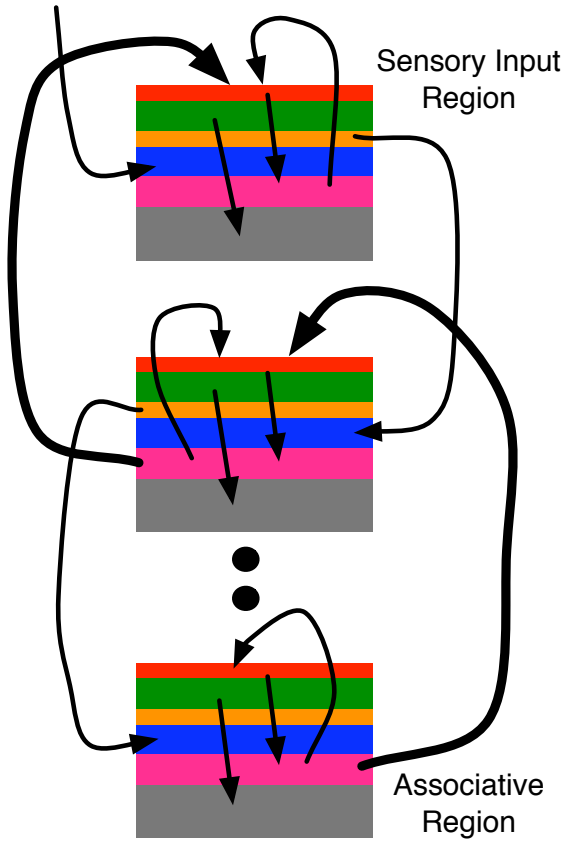
Cerebellum & BG



Hippocampus



NeoCortex



Comparative Anatomy for Prediction

1. CB & BG have dedicated tracts without much overlap. Context $\rightarrow$ action.
2. HC & Cortical areas have massive interconnections and recurrence that support:
   - Spreading activation for recall, information integration, concept formation and declarative prediction.
   - Maintenance of activity patterns for conscious attention

Prediction & Cognitive Incrementalism

- Prediction is essential for sensorimotor behavior.
- But a lot of that is done using procedural predictive mechanisms.
- Cognition may build on this, since procedural areas support basic aspects of cognition: timing, focus of attention, etc.
- But high-level cognition requires declarative prediction, handled by evolutionarily newer brain regions.
- The hippocampus could be pivotal for cognitive incrementalism:
  - Essential for both navigation (a sensorimotor act with varying cognitive demands) and declarative memory formation.
  - Theta phase precession useful in concept formation and general sequence learning.

Related Articles

- Downing (2009).*Predictive models in the brain*. **Connection Science**, 21(1), pp. 39-74.
- Downing (2007). *Neuroscientific implications for situated and embodied AI*. **Connection Science**, 19(1), pp.75-104.
- Downing (2005). *The predictive basis of situated and embodied AI*. **GECCO Proceedings**, pp. 43-50.

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