

Motor Control and Reinforcement Learning

Computational Cognitive Neuroscience

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Learning Rules Across the Brain

Area	Learning Signal			Dynamics		
	Reward	Error	Self Org	Separator	Integrator	Attractor
Primitive Basal Ganglia	+++	- - -	- - -	++	-	- - -
Cerebellum	- - -	+++	- - -	+++	- - -	- - -
Advanced Hippocampus	+	+	+++	+++	- - -	+++
Neocortex	++	+++	++	- - -	+++	+++

Legend:
 + = has to some extent ... +++ = defining characteristic – definitely has
 - = not likely to have ... - - - = definitely does not have

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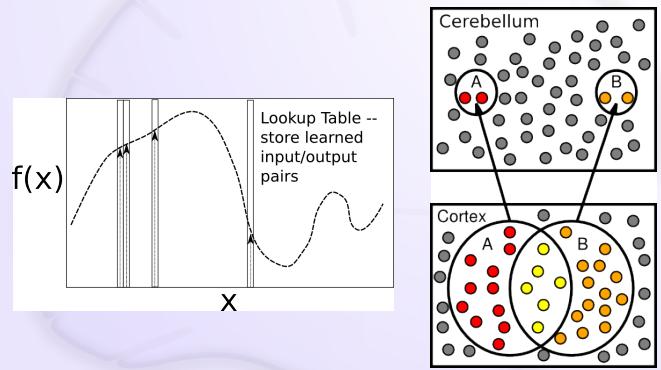
Primitive, Basic Learning..

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Primitive Basal Ganglia	+++	- - -	- - -	++	-	- - -
Cerebellum	- - -	+++	- - -	+++	- - -	- - -

- Reward & Error = most basic learning signals (self organized learning is a luxury..)
- Simplest general solution to any learning problem is a *lookup table* = separator

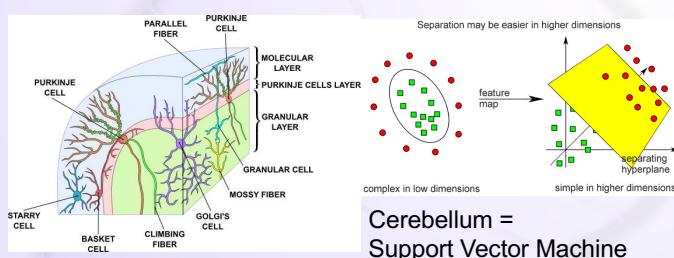
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Lookup Table & Pattern Separation



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Cerebellar Error-driven Learning



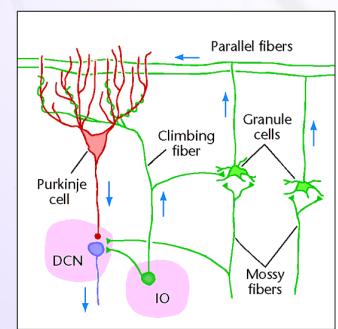
- Granule cells = high-dimensional encoding (separation)
- Purkinje/Olive = delta-rule error-driven learning
- Classic ideas from Marr (1969) & Albus (1971)

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Cerebellum is Feed Forward

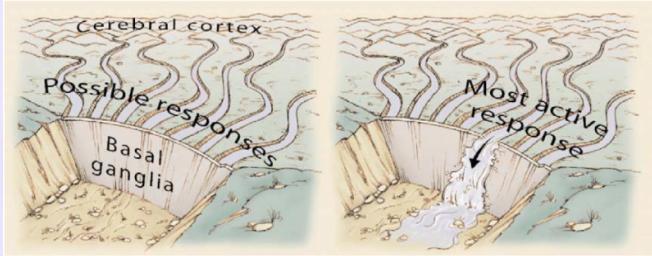
Feedforward circuit:

- Input (PN) \rightarrow granules \rightarrow Purkinje \rightarrow Output (DCN)
- Inhibitory interactions – no attractor dynamics
- Key idea: does delta-rule learning bridging small temporal gap:
 $S(t-100) \rightarrow R(t)$
 $\wedge \text{Error}(t+100)$



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Basal Ganglia and Action Selection



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Two Competing Pathways



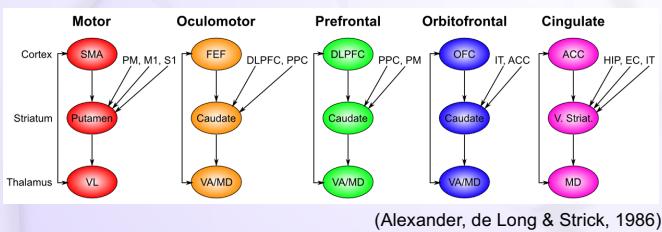
Positive dopamine reinforces Go!



Negative dopamine reinforces No Go!



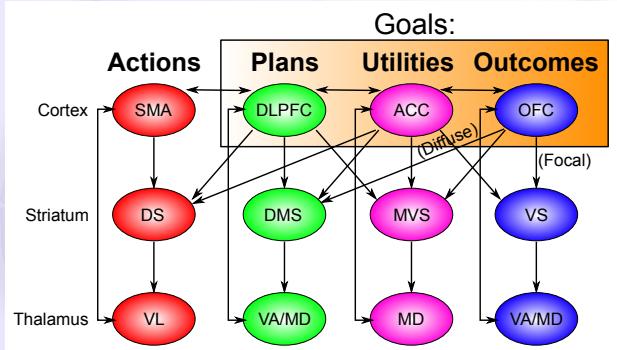
Basal Ganglia: Action Selection



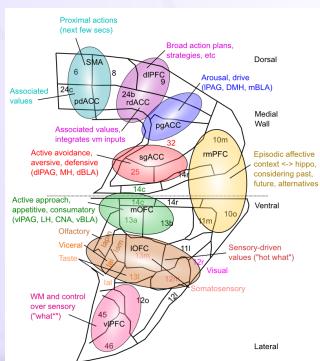
- Selects motor and “cognitive” actions across frontal areas

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Chain of Command..

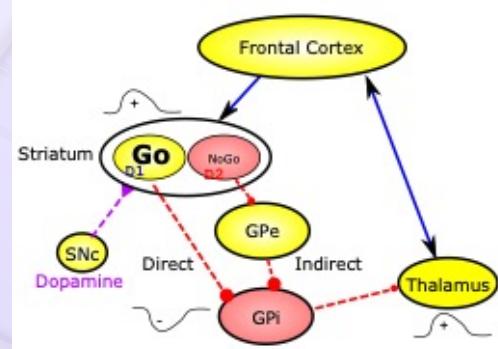


Medial Frontal Map of Values



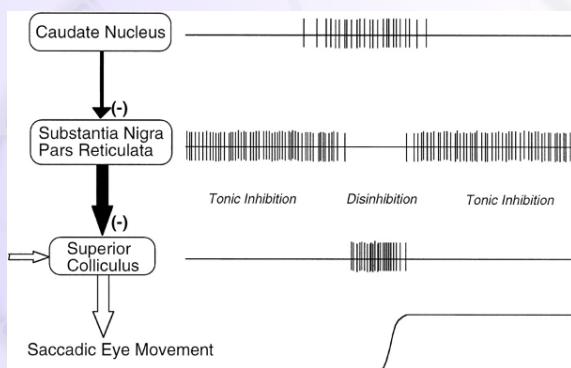
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Release from Inhibition



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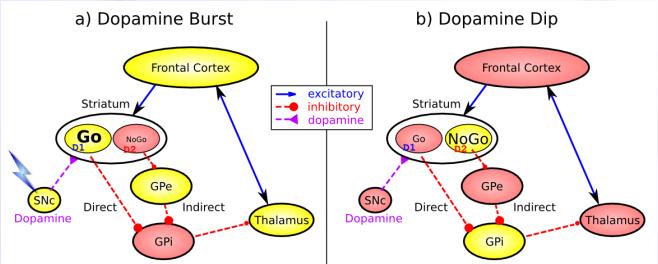
Release from Inhibition



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Basal Ganglia Reward Learning

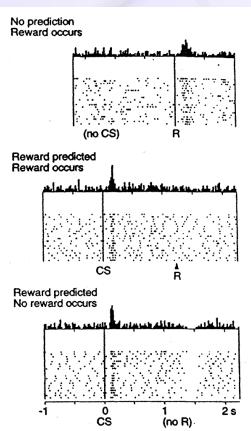
(Frank, 2005...; O'Reilly & Frank 2006)



- Feedforward, modulatory (disinhibition) on cortex/motor (same as cerebellum)
- Co-opted for higher level cognitive control → PFC

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Reinforcement Learning: Dopamine



Rescorla-Wagner / Delta Rule:

$$\begin{aligned} \bullet \delta &= r - \hat{r} \\ \bullet \delta &= r - \sum xw \end{aligned}$$

But no CS-onset firing – need to Anticipate the future!

$$\bullet \delta = (r + f) - \hat{r}$$

CS-onset = future reward = f

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Temporal Differences Learning

$$\bullet V(t) = r(t) + \gamma^1 r(t+1) + \gamma^2 r(t+2) \dots$$

$$\bullet \hat{V}(t) = r(t) + \gamma \hat{V}(t+1)$$

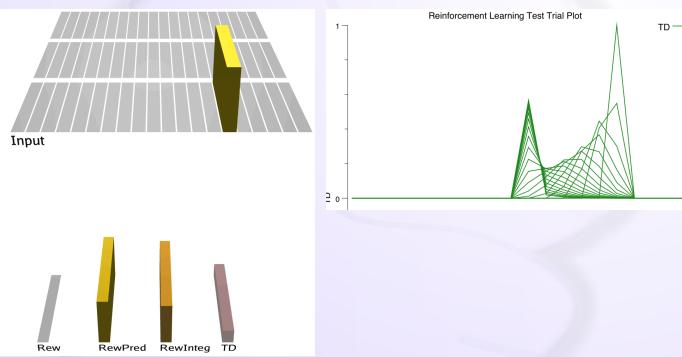
$$\bullet 0 = (r(t) + \hat{V}(t+1)) - \hat{V}(t)$$

$$\bullet \delta = (r(t) + \hat{V}(t+1)) - \hat{V}(t)$$

$$\bullet f = \gamma \hat{V}(t+1) \quad \text{← this is the future!}$$

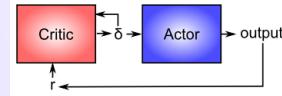
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Network Implementation

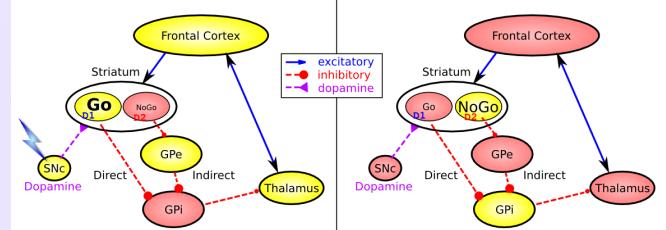


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Actor - Critic

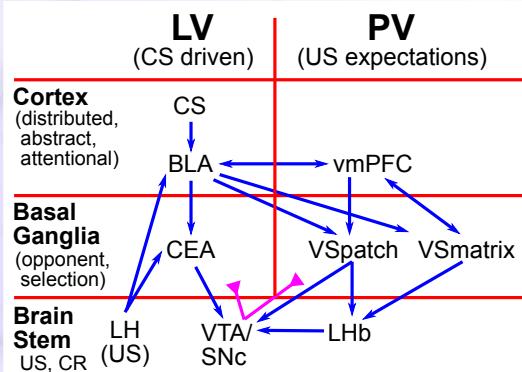


a) Dopamine Burst



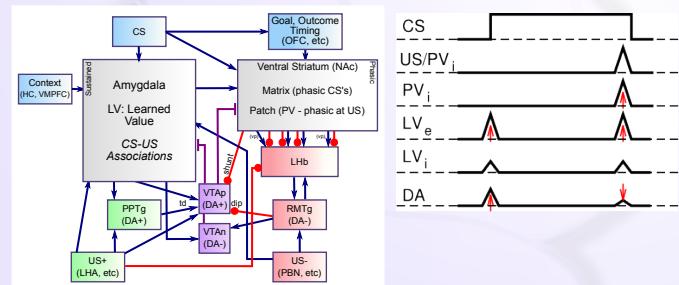
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Biology of Dopamine



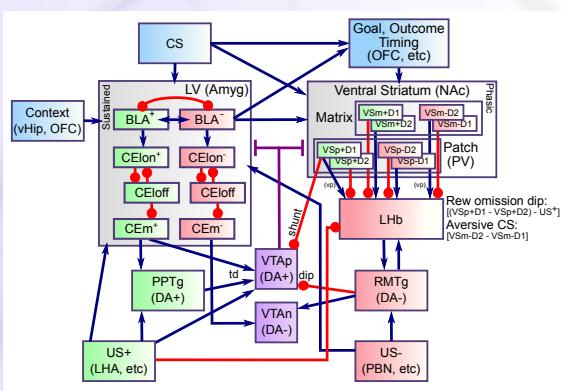
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Biology of Dopamine: PVLV



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Biology of Dopamine



Mollck et al, in press

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BG + Cerebellum Capacities

- Learn what satisfies basic needs, and what to avoid (BG reward learning)
 - And what information to maintain in working memory (PFC) to support successful behavior
- Learn basic Sensory → Motor mappings accurately (Cerebellum error-driven learning)
 - Sensory → Sensory mappings? (what is going to happen next..)

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BG + Cerebellum Incapacities

- Generalize knowledge to novel situations
 - Lookup tables don't generalize well..
- Learn abstract semantics
 - Statistical regularities, higher-order categories, etc
- Encode episodic memories (specific events)
 - Useful for instance-based reasoning
- Plan, anticipate, simulate, etc..
 - Requires robust working memory