Motor Control and Reinforcement Learning

Computational Cognitive Neuroscience

Randall O'Reilly

Learning Rules Across the Brain

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

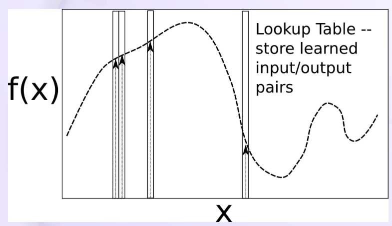
+ = has to some extent … +++ = defining characteristic – definitely has
- = not likely to have … - - - = definitely does not have

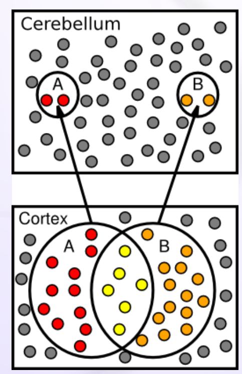
Primitive, Basic Learning..

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

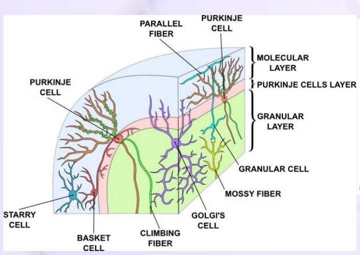
- Reward & Error = most basic learning signals (self organized learning is a luxury..)
- Simplest general solution to any learning problem is a *lookup table* = separator

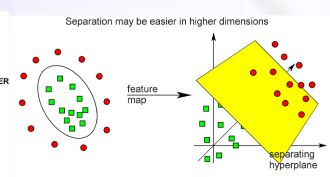
Lookup Table & Pattern Separation





Cerebellar Error-driven Learning





Cerebellum = Support Vector Machine

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

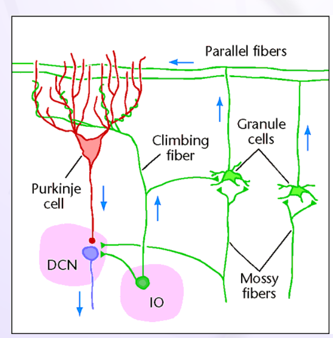
Cerebellum is Feed Forward

Feedforward circuit:

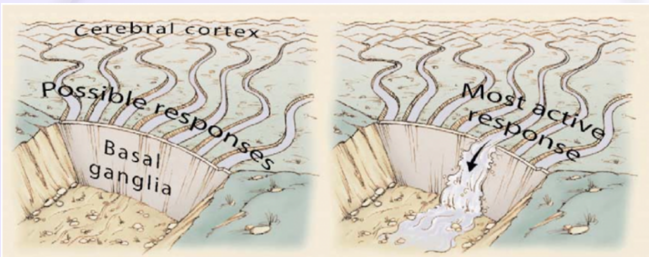
- Input (PN) -> granules -> Purkinje -> Output (DCN)
- Inhibitory interactions – no attractor dynamics
- Key idea: does delta-rule learning bridging small temporal gap:

  S(t-100) -> R(t)

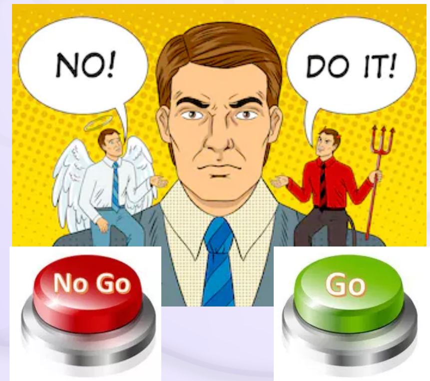
  ^ Error(t+100)



Basal Ganglia and Action Selection



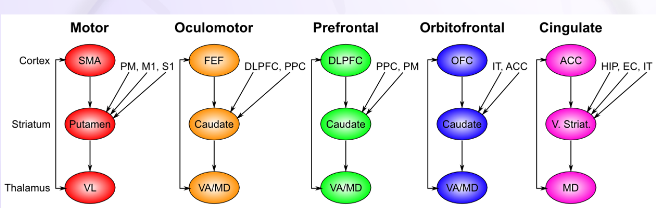
Two Competing Pathways



Positive dopamine reinforces Go!

Negative dopamine reinforces No Go!

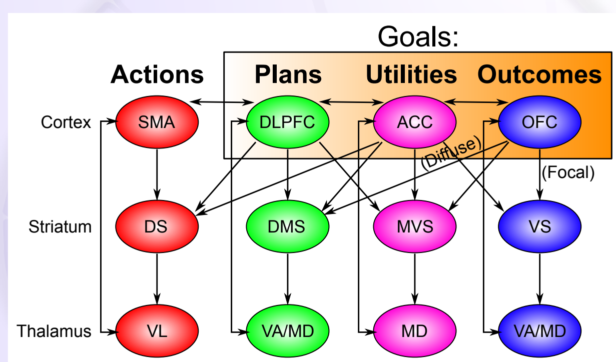
Basal Ganglia: Action Selection



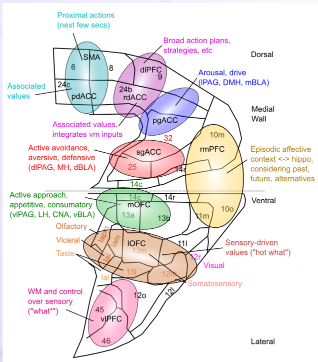
(Alexander, de Long & Strick, 1986)

- Selects motor and “cognitive” actions across frontal areas

Chain of Command..



Medial Frontal Map of Values



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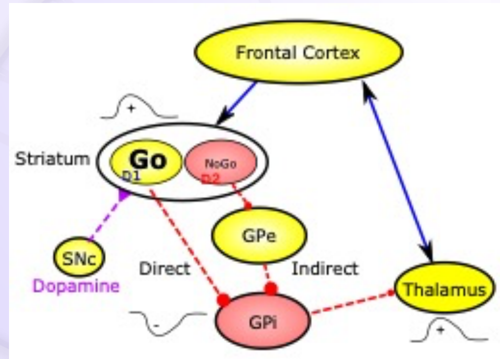
Release from Inhibition



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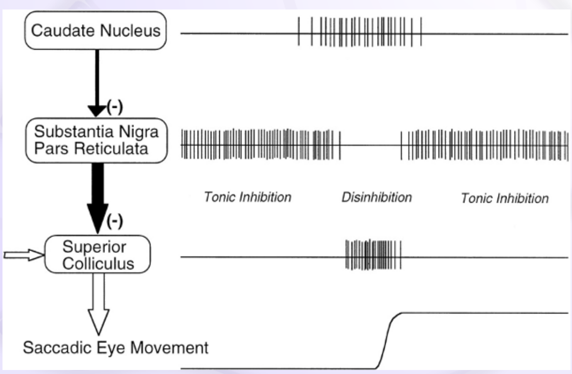
Release from Inhibition



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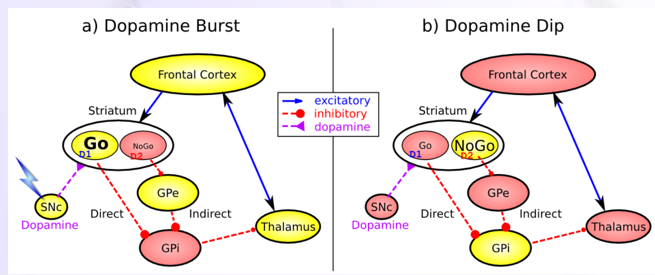
Basal Ganglia Reward Learning

(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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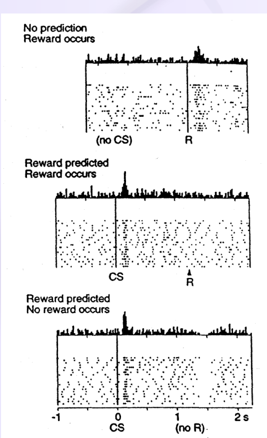
Reinforcement Learning: Dopamine



Rescorla-Wagner / Delta Rule:

- $\delta = r - \hat{r}$
- $\delta = r - \sum xw$

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

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

CS-onset = future reward = f

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Temporal Differences Learning

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

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

$$0 = \left(r(t) + \gamma \hat{V}(t+1)\right) - \hat{V}(t)$$

$$\delta = \left(r(t) + \gamma \hat{V}(t+1)\right) - \hat{V}(t)$$

$$f = \gamma \hat{V}(t+1)$$ <- this is the future!

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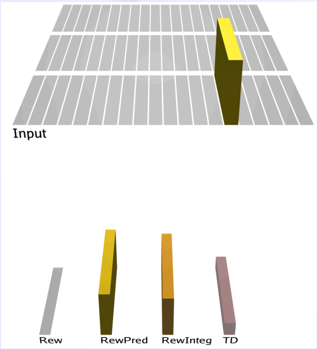
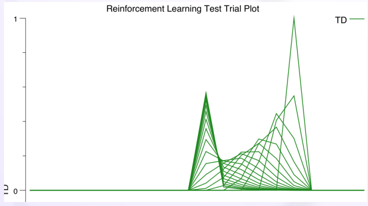
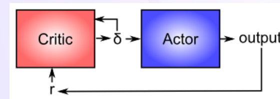
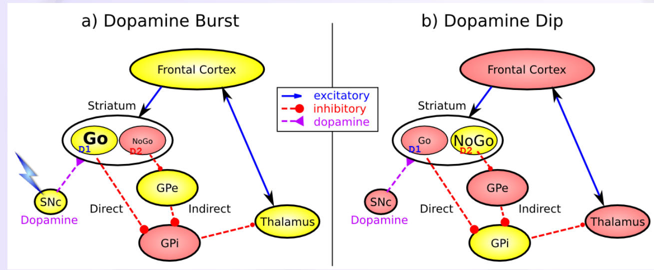
Network Implementation



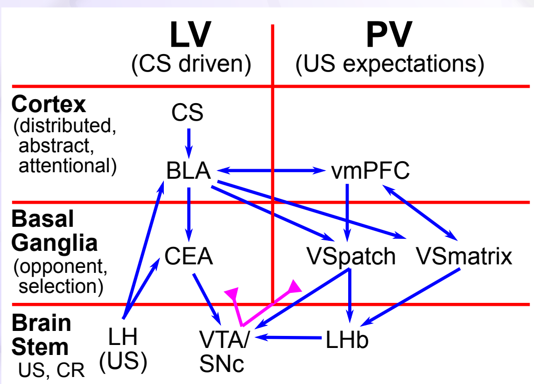


Actor - Critic

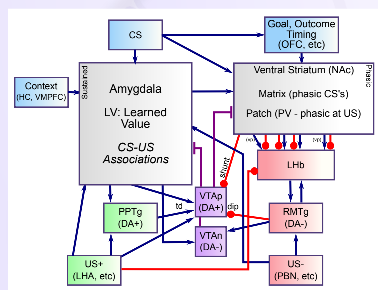


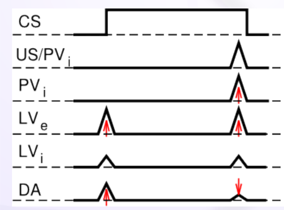


Biology of Dopamine



Biology of Dopamine: PVLV





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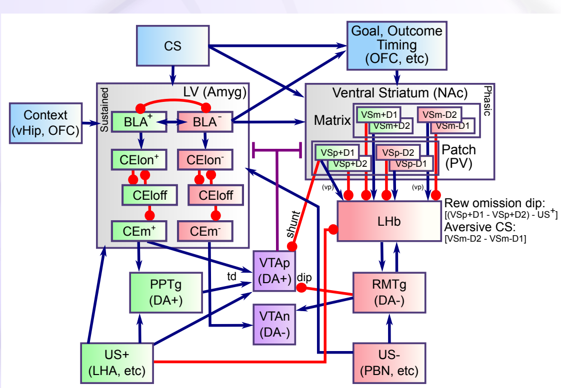

Mollick et al, in press

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..)

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