# Motor Control and Reinforcement Learning

Computational Cognitive Neuroscience

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## Learning Rules Across the Brain

| Area | Learning Signal: Reward | Error | Self Org | Separator | Dynamics: 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

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## Primitive, Basic Learning..

| Area | Learning Signal: Reward | Error | Self Org | Separator | Dynamics: 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

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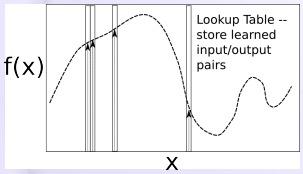
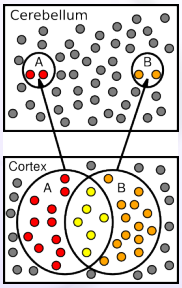
## Lookup Table & Pattern Separation

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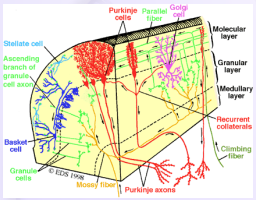
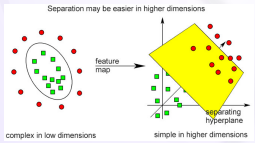
## Cerebellar Error-driven Learning




Cerebellum = Support Vector Machine

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

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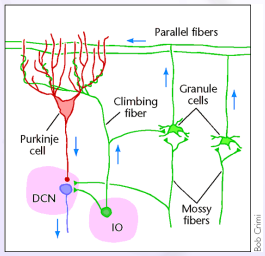
## Cerebellum is Feed Forward

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)

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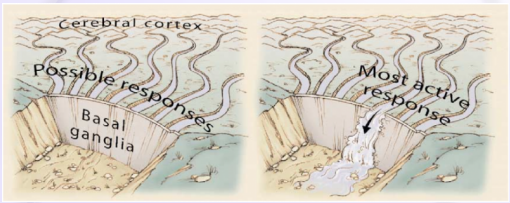
## Basal Ganglia and Action Selection

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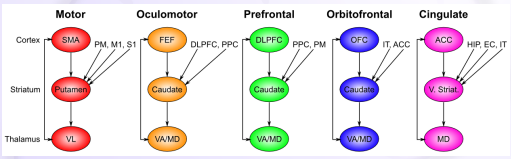
## Basal Ganglia: Action Selection




- Selects motor and "cognitive" actions across frontal areas

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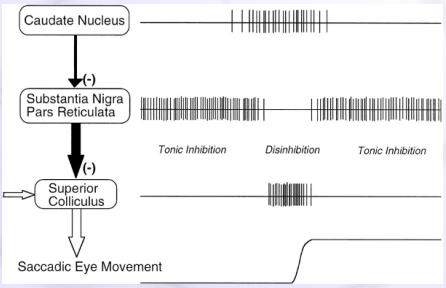
## Release from Inhibition

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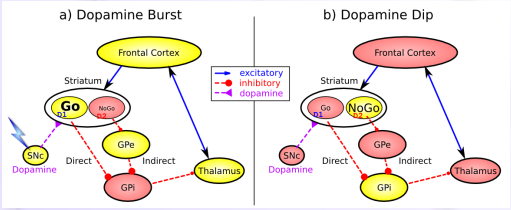
## Basal Ganglia Reward Learning

(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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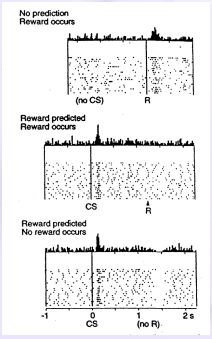
## Reinforcement Learning: Dopamine




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

- $V(t) = r(t) + \gamma^1 r(t+1) + \gamma^2 r(t+2)...$
- $\hat{V}(t) = r(t) + \gamma \hat{V}(t+1)$
- $0 = \left(r(t) + \hat{V}(t+1)\right) - \hat{V}(t)$
- $\delta = \left(r(t) + \hat{V}(t+1)\right) - \hat{V}(t)$
- $f = \gamma \hat{V}(t+1)$ <- this is the future!

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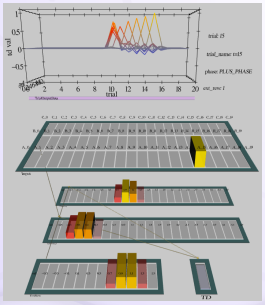
## Network Implementation



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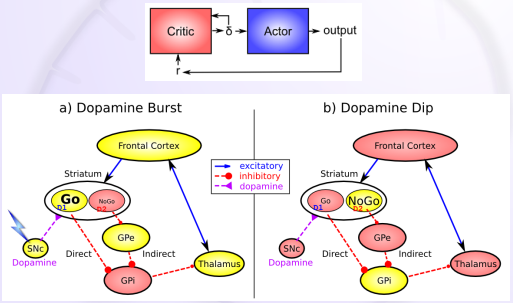
## Actor - Critic

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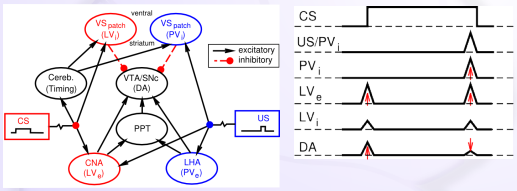
## Biology of Dopamine

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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

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