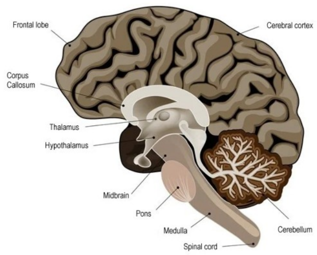
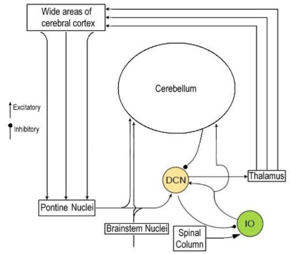
Go Configure

What is the cerebellum doing?
Can PCT model it?





Bruce Nevin
IAPCT 2022

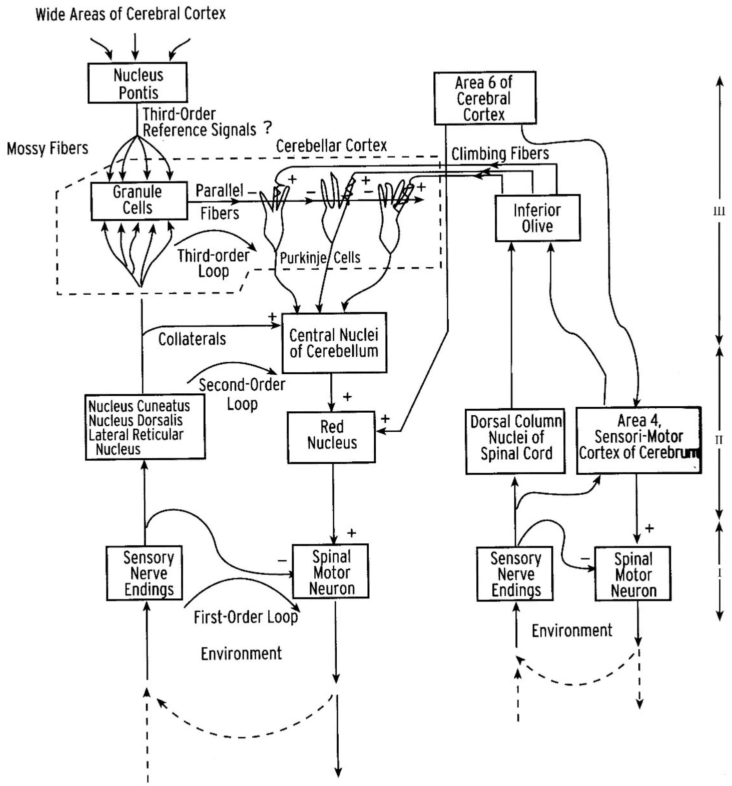
Promise of PCT

The organism is a black box
A PCT model is a white box
If a simulation replicates [numerical measures of] behavior
control structures in the model predict
control structures in the organism

PCT can provide

- **Guidance for lines of neuroscience research**
- **Organizing principles to help explain neuroscience findings**

Didn’t Bill already model it?



B:CP **‘configuration control’**

- 1969 neuroscience
- Some fundamental errors
- Limited to motor control

‘Artificial cerebellum’

- Stabilizes a control system
  e.g. motor control in ‘little man’
- Uses the convolution theorem instead of e. coli reorganization
- Method used to sharpen visual images
- Adaptive filter (Dean et al. 2010)

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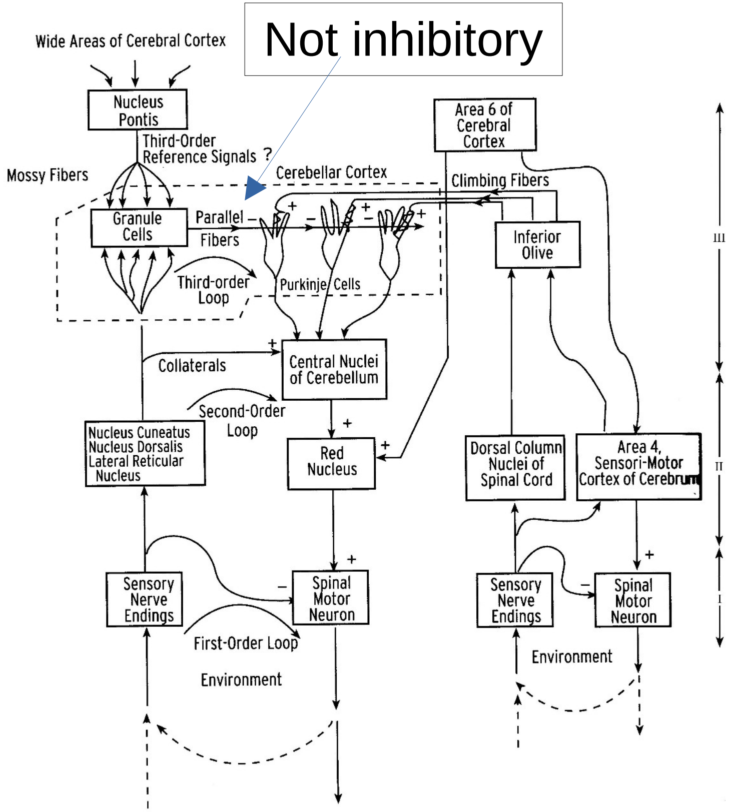

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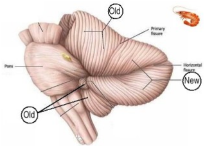
Did not update the neuroscience parallel



Motor & somatic control

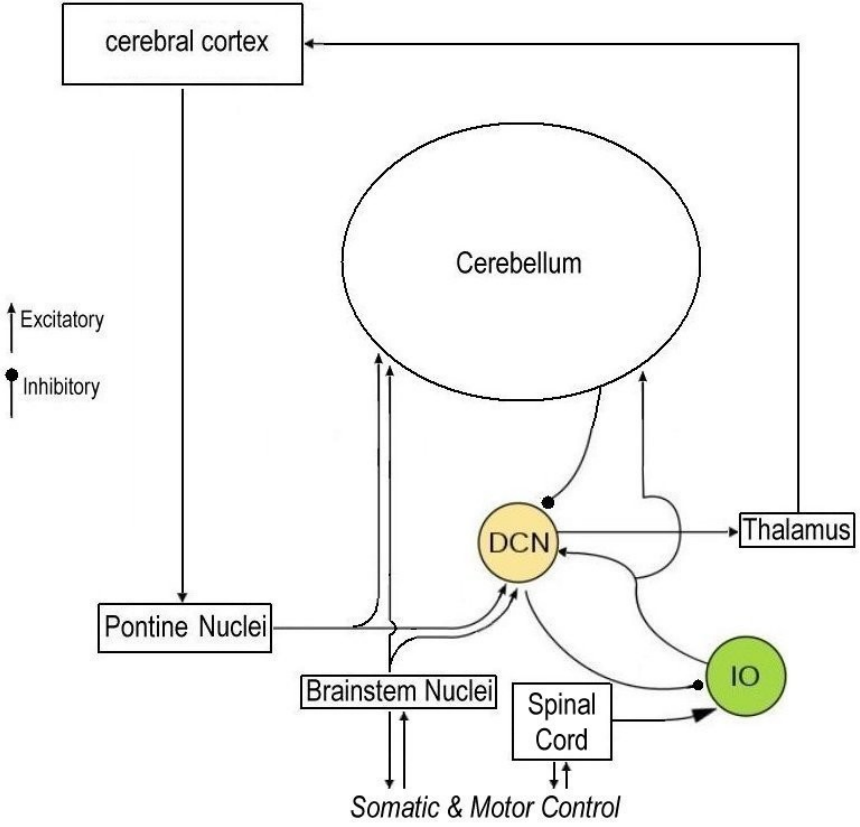
Three loops through DCN

- Motor: spinal cord via Inferior Olive (IO)
- Somatic: brainstem
- ‘Planning’: cerebrum, pons, & Thalamus

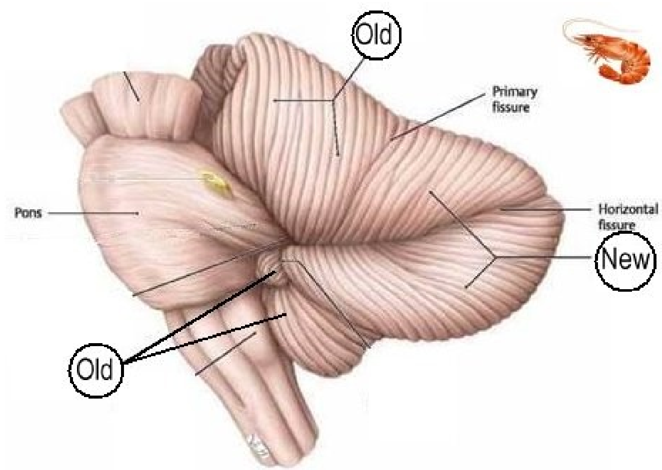
Each loop signal is copied to cerebellum

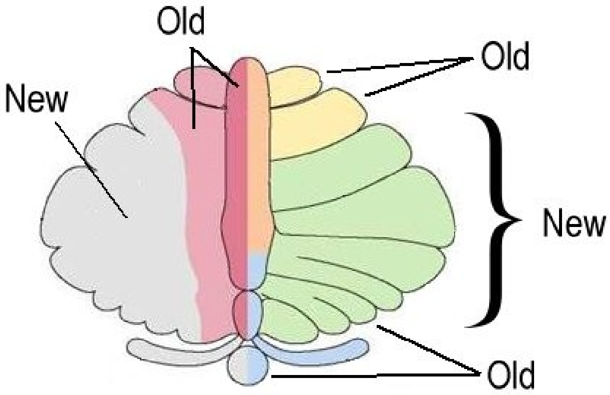
Each cerebellar output inhibits
one neuron passing through DCN

DCN looks like a collection of comparators



Evolution beyond motor control





Evolutionary expansion

- Vertebrates: motor control
- Mammals: more social & emotional
- Primates: more cognitive
- Humans: many levels
  Cognitive development after 17 months

In humans
10% of whole brain (5% in infant)
80% of neurons in brain
80% of brain’s surface area

Higher levels of control

Add more signals to cerebral loop

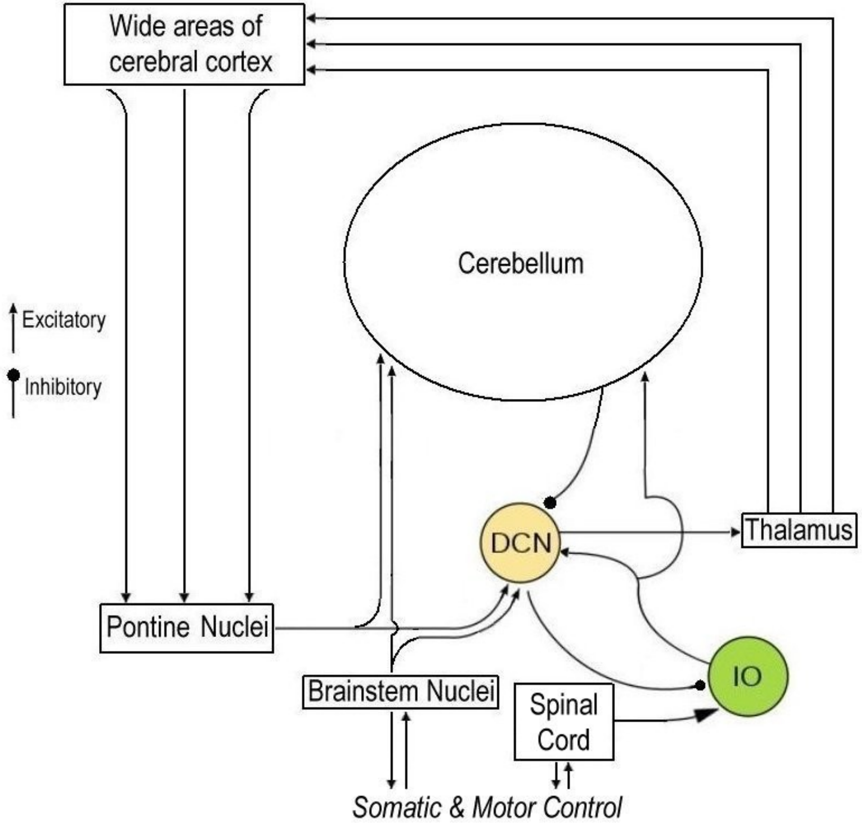
Each loop signal is copied to cerebellum

Regions of cerebellum functionally distinct

Each cerebellar (Purkinje) output inhibits one neuron passing through DCN

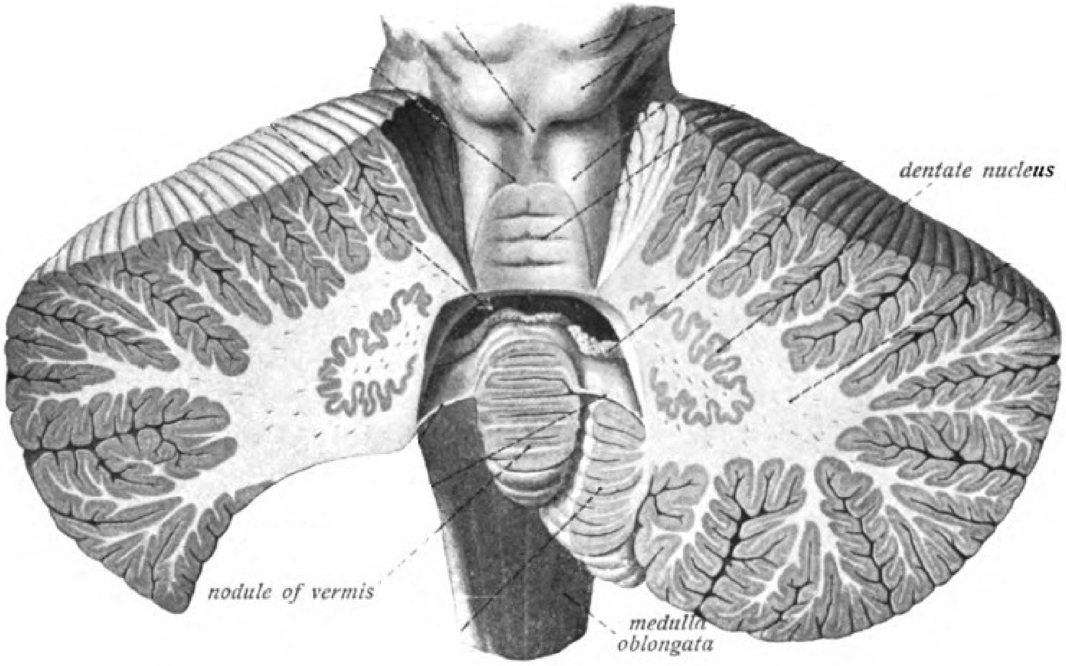
Same neuron?

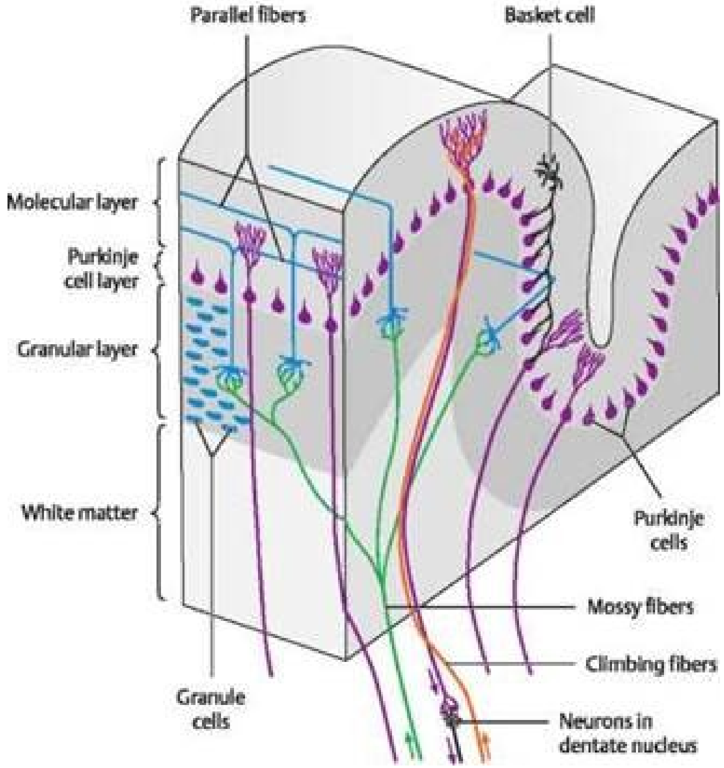
DCN looks like a collection of comparators



Uniform matrix architecture

80% of human brain's surface area





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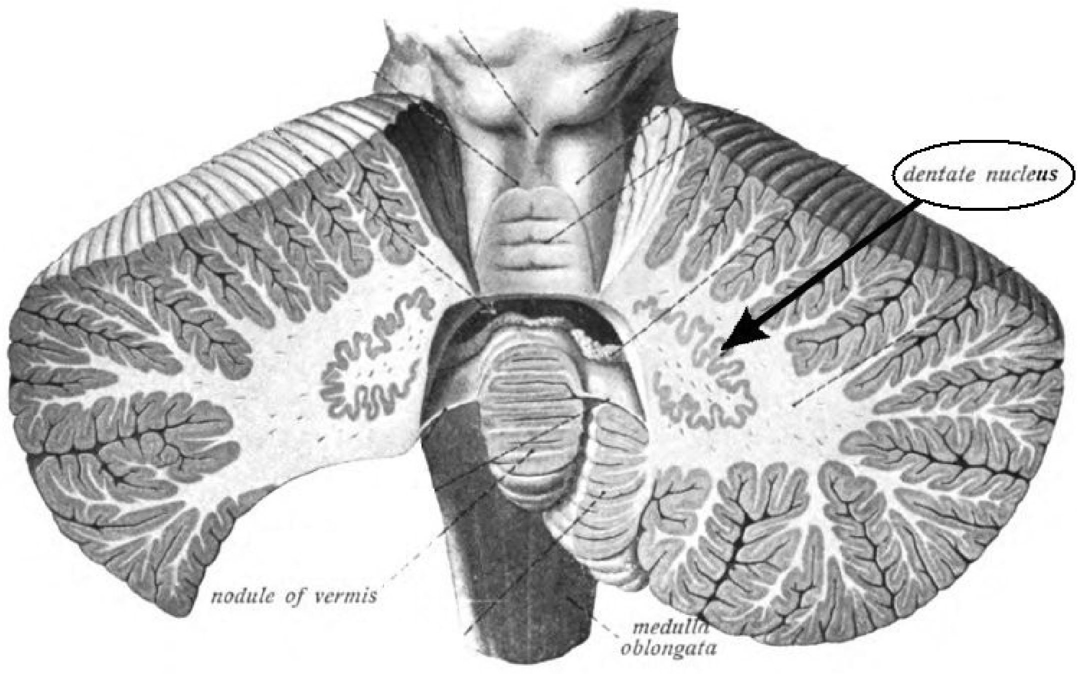
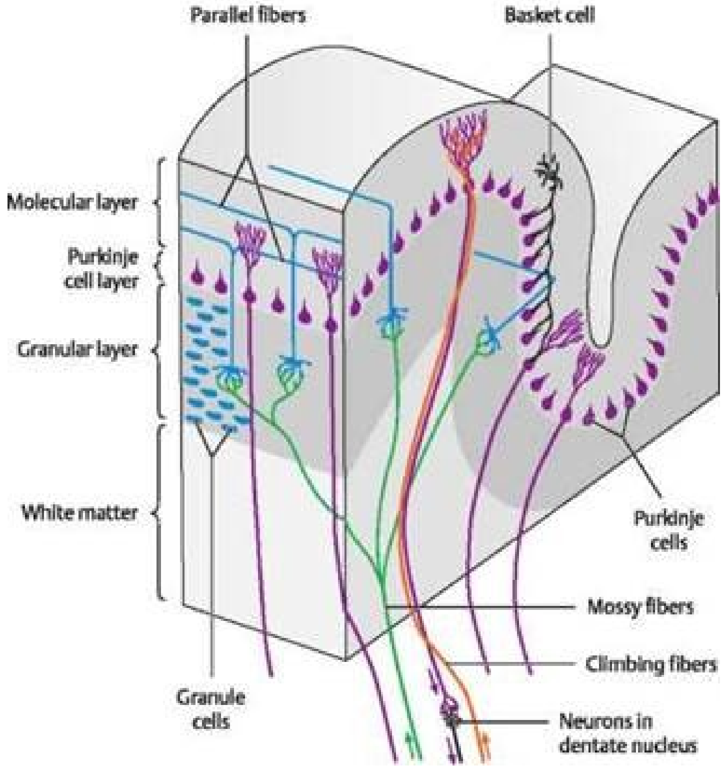
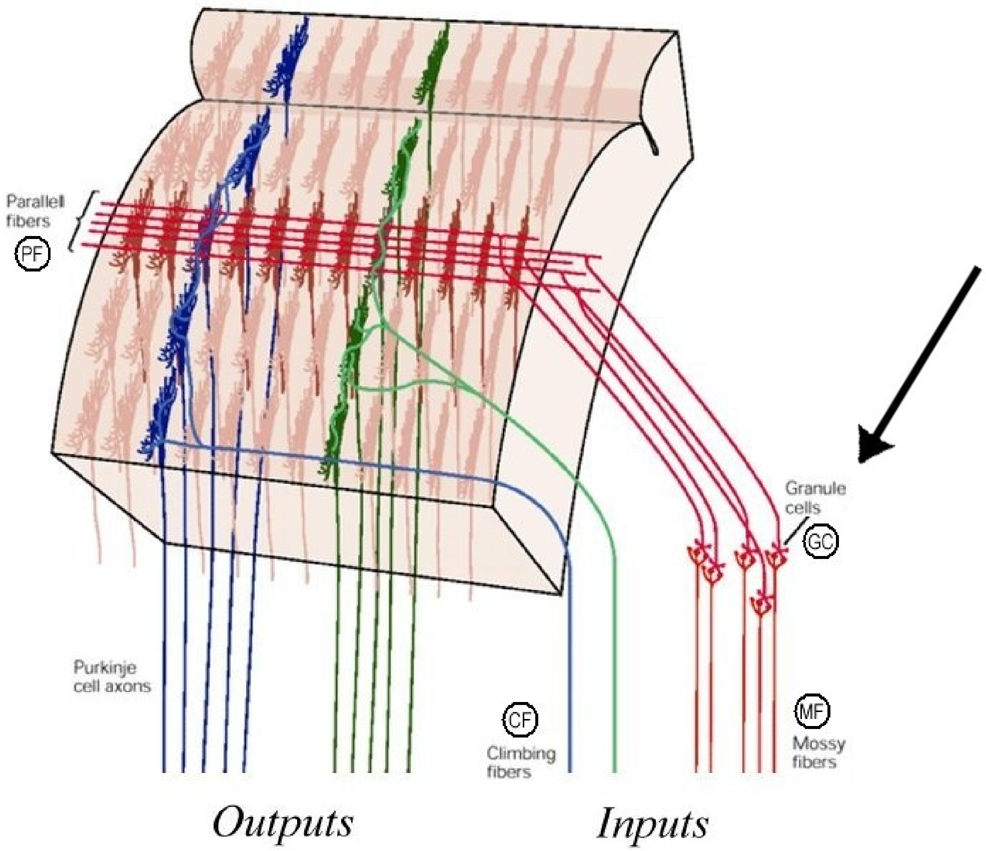




DCN, Pons, etc. also have evolved expansions

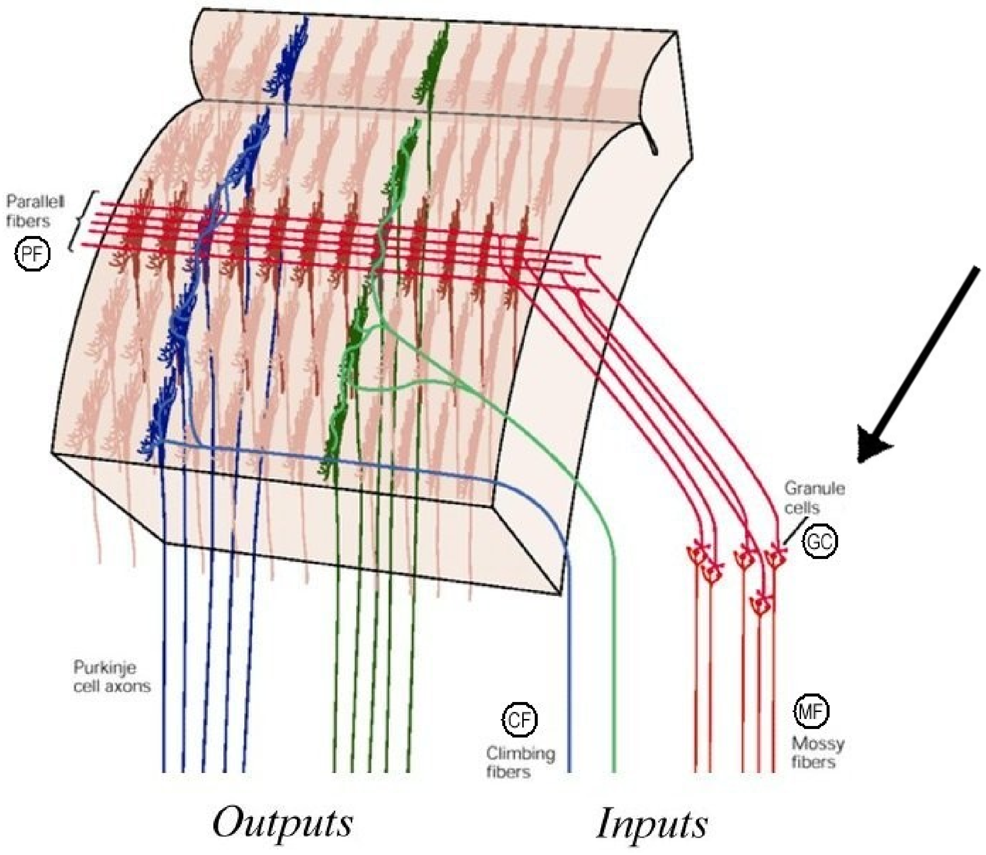
Modulation of the cerebral loops



Granule cells (GC)

- Densely packed in the granular layer
- Among smallest in brain
- 75% of brain's neurons (~50B)
- ~200 GC/MF
- Input from 4-5 MFs
- Inhibit MF excitation of PCs
- Each PC contacted indirectly by thousands of MFs

Modulation of the cerebral loops



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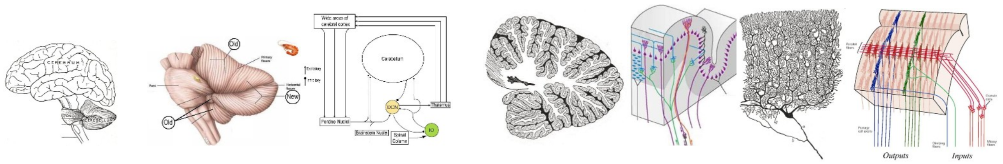
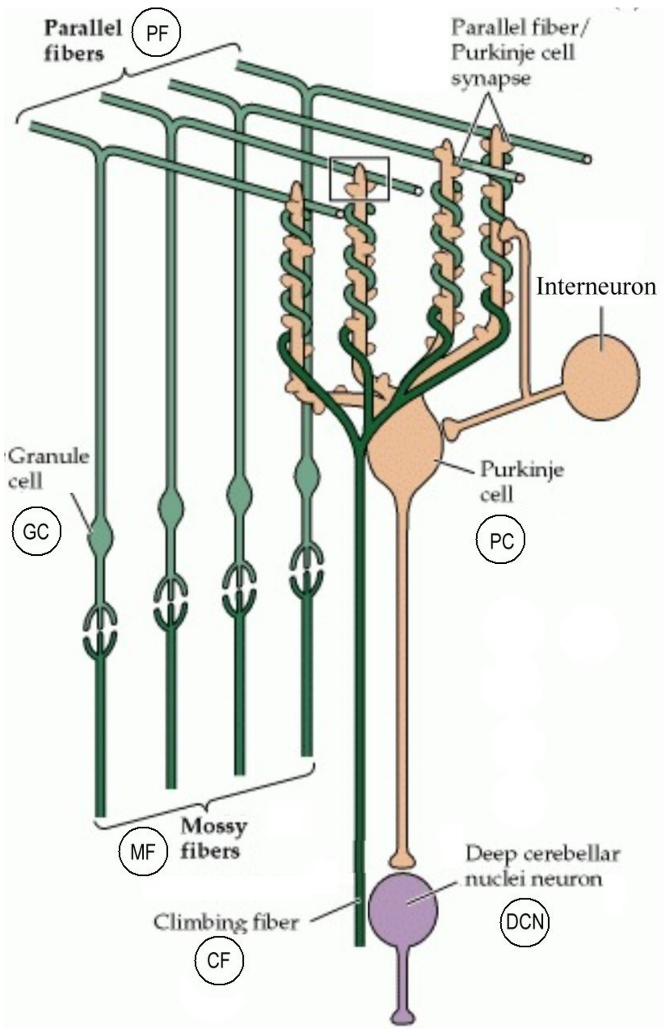
Hard to figure out what GCs do
A PCT model could guide them

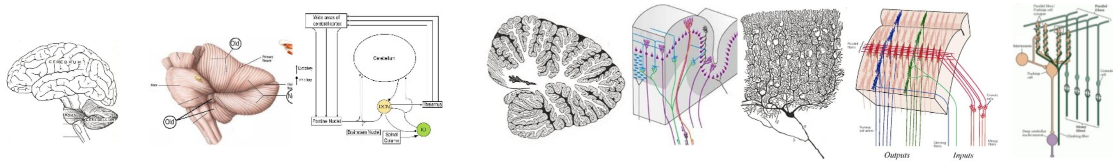


CF Inputs from spinal cord (motor)
- Each CF excites ~30,000 synapses in 1 PC
- ‘Complex spikes’ ~1/s
- Among strongest in the nervous system

MF/PF input from Cerebrum via Pons
- Each PF excites ~150,000 PCs
- ~175,000 PF synapses on each PC
- ‘Simple spikes’ 50-100/s
- PF unmyelinated (ephaptic synchronization)

PC axon
- The only output of cerebellum
- inhibits one neuron in a deep cerebellar nucleus (DCN)





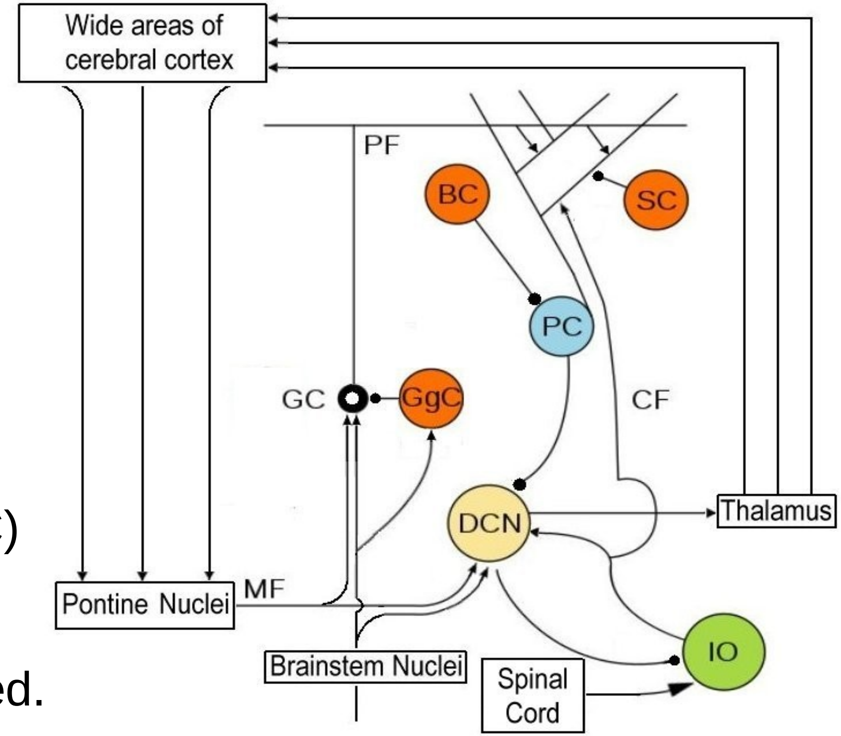
Interneurons inhibit specific PCs

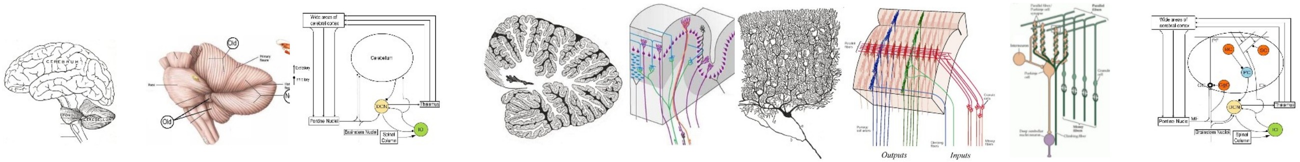
- Basket cells inhibit PC soma
- Stellate cells inhibit PC dendrite tree

These are instrumental in learning. Inhibiting a particular Purkinje cell leaves uninhibited the signal in the neuron in the DCN to which its axon connects.

- Each Golgi cell inhibits ~1K granule cells (GC) (MF & PF inputs)

They then transmit MF signals to PFs uninhibited.



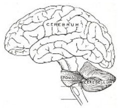
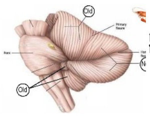
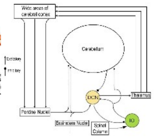
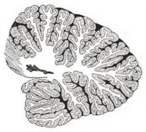
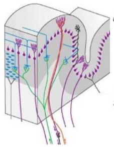
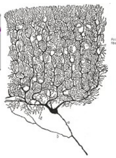
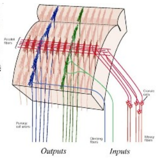


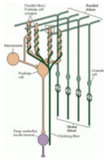
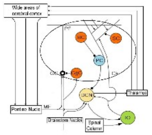
Matrix structure is invariant across the cerebellum.

It serves all levels, motor & cerebral.

The deep cerebellar nuclei (DCN) look like collections of comparators.

What does this matrix structure do?

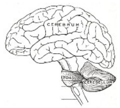
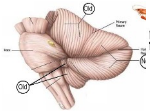
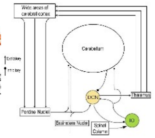
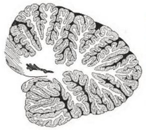
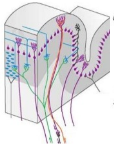
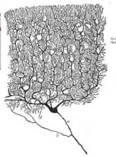
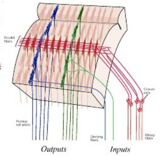



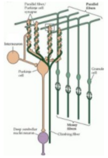
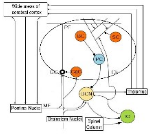
Configuration control (Bill’s conjecture)

- Pattern recognition: “abstracts *invariant relations* among lower-level signals” *
- Faster firing = “more of” e.g. elbow-bend or head-turn *relation*
- Invariant *relations* even as configuration rotates, translates, etc.

* Definition of configurations, *B:CP* p. 122.

What does this matrix structure do?

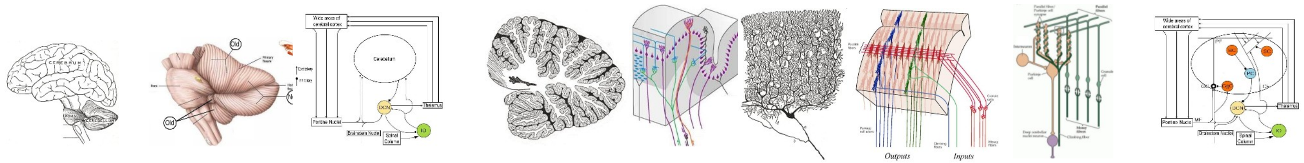








An input function (my conjecture)

- Many-one transformation between levels
- Pattern-recognition functions “abstract invariant relationships” among lower-level signals. (Definition of configurations, *B:CP* p. 122)
- Invariant *relationships* even as a configuration rotates, translates, etc.

What does this matrix structure do?



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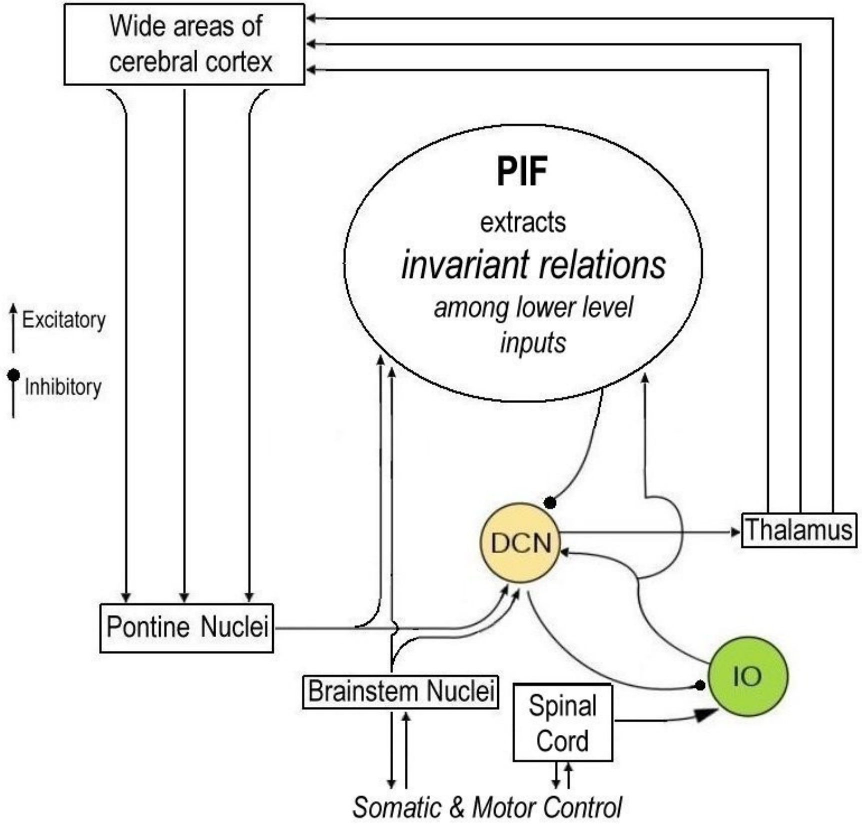
Consistent with facts of evolution and maturation

Transforms level to level

Enter DCN (2x)	*Exit Thalamus*
Sensations	→ Configuration
Configurations	→ Relationship
Relationships	→ Category

Imagined configurations, relationships, etc.
→ Abstract concepts

Concepts	→ Principles
Principles	→ System concepts



Model motor control to model all

Extract higher-level perception
from lower-level inputs

Enter DCN (+-)	*Exit Thalamus*
Sensations	→ Configuration
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Imagined configurations, relationships, etc.

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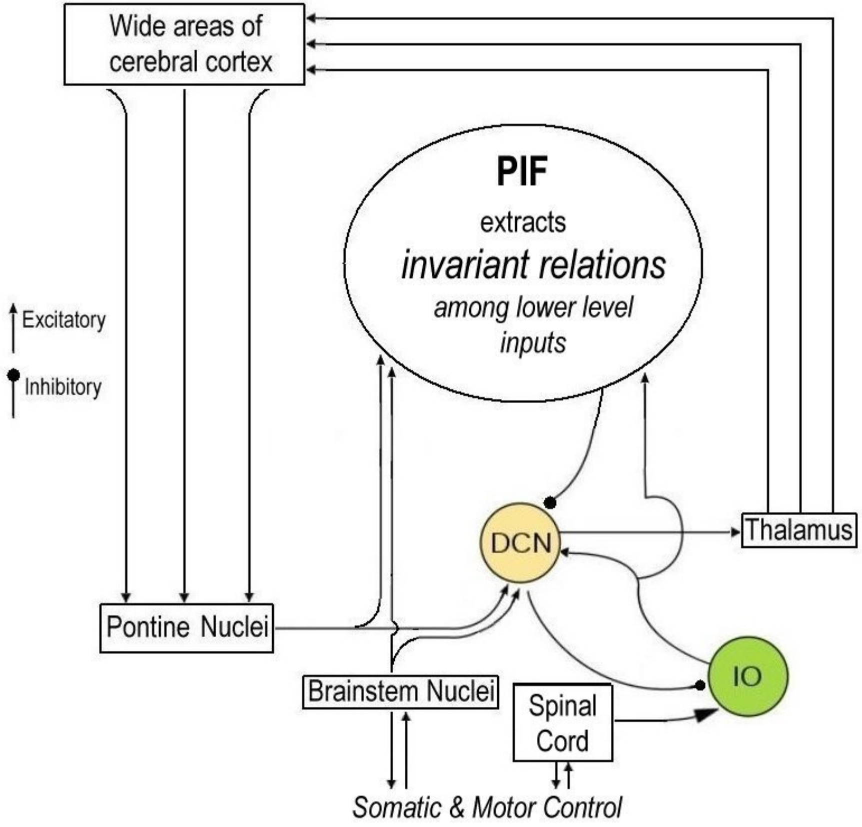
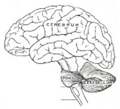
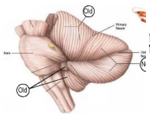
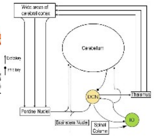
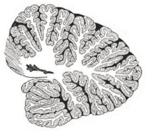
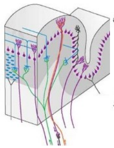
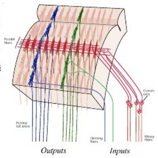
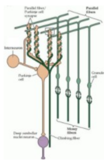
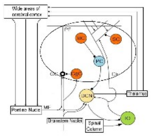
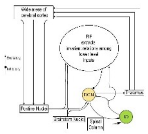
More cognitive development is open-ended.

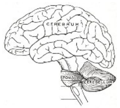
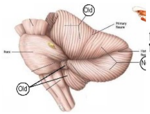
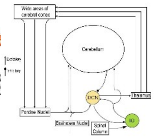
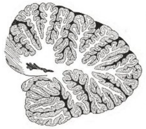
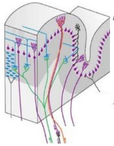
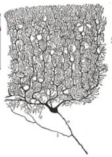
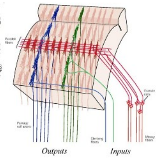


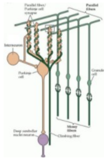
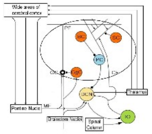
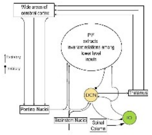






New toys

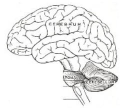
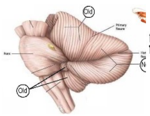
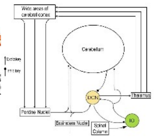
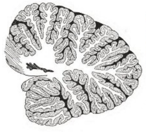
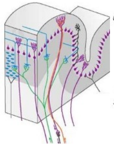
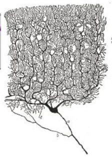
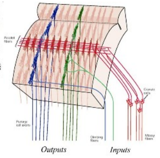
Questions?

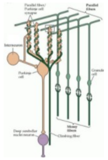
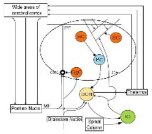
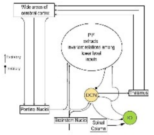








Backup Slides

Can PCT model it?

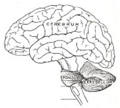
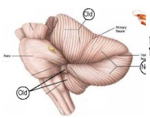
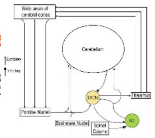
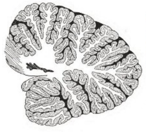
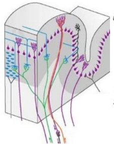
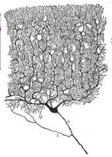
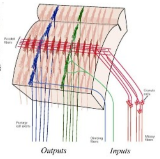








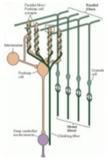
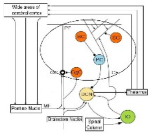
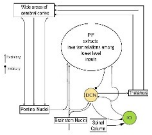




… The primate cerebellum contributes not only to motor control, but also to higher ‘cognitive’ function. However, there is no consensus about how .... The answer [is] in the nature of cerebellar connections to areas of the cerebral cortex … and in the uniformity of its intrinsic cellular organization, which implies uniformity in information processing regardless of the area of origin in the cerebral cortex. … models of how the cerebellum processes information from the motor cortex might be extended to explain how it could also process information from the prefrontal cortex.

—Narender Ramnani (2006)

Bill’s ‘Artificial cerebellum’

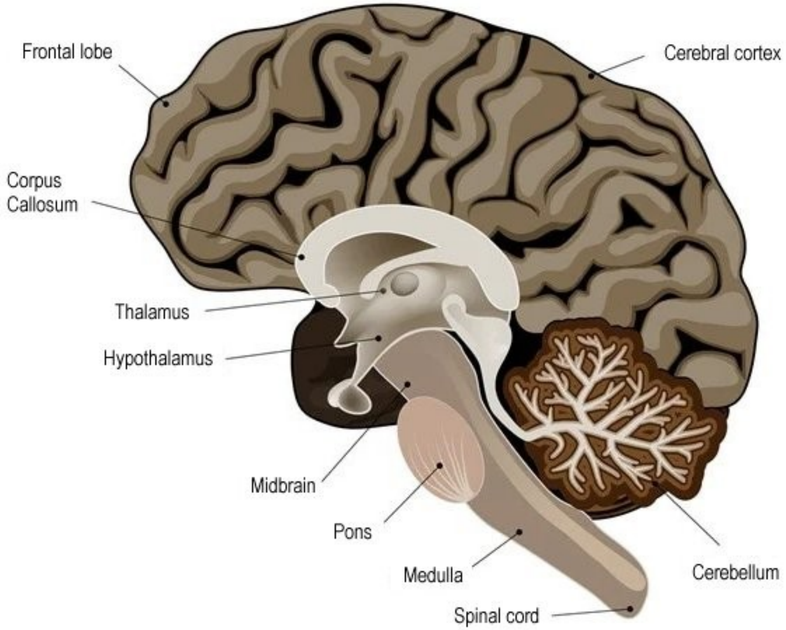
      

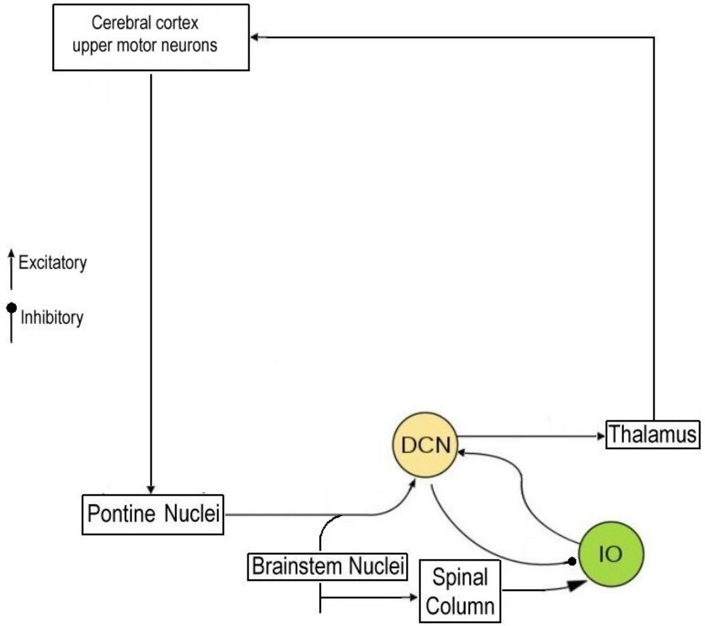
  

I have long said that higher systems may well act by varying the parameters of lower systems as well as their reference signals. […] I proposed a model in which an auxiliary control system (whether you should consider it “higher” or not is debatable) changes the weightings in an output function in a way that emulates the convolution theorem. It worked pretty well when embedded in the Little Man model. I called this model the “artificial cerebellum,” because of some resemblances of the algorithm to processes known to happen in the cerebellum. ... However, my modeling efforts focus on what kind of control process is done, which doesn’t depend on guessing which part of the brain does it.

—Bill Powers
5:08pm 27 June 2003 CSGnet Archive
http://discourse.iapct.org/t/ruminations-on-importance/10094/6

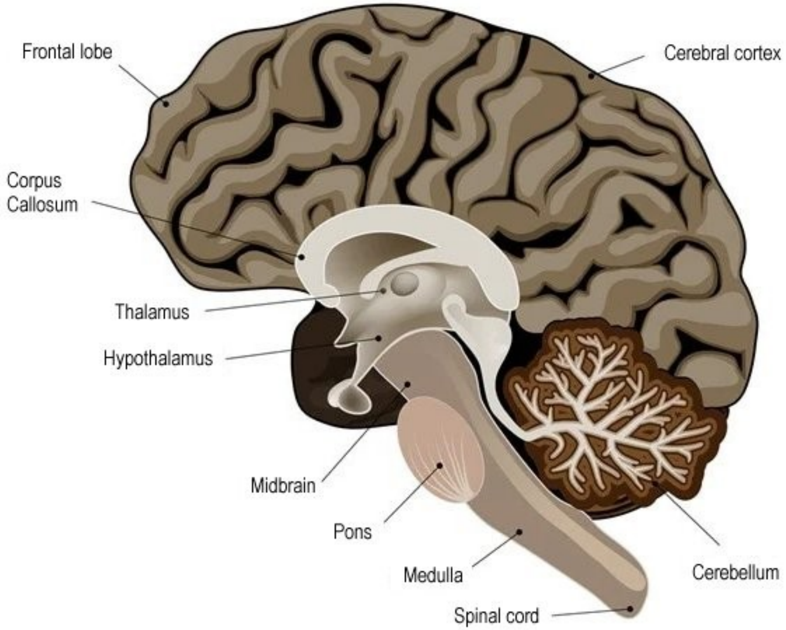
Motor control

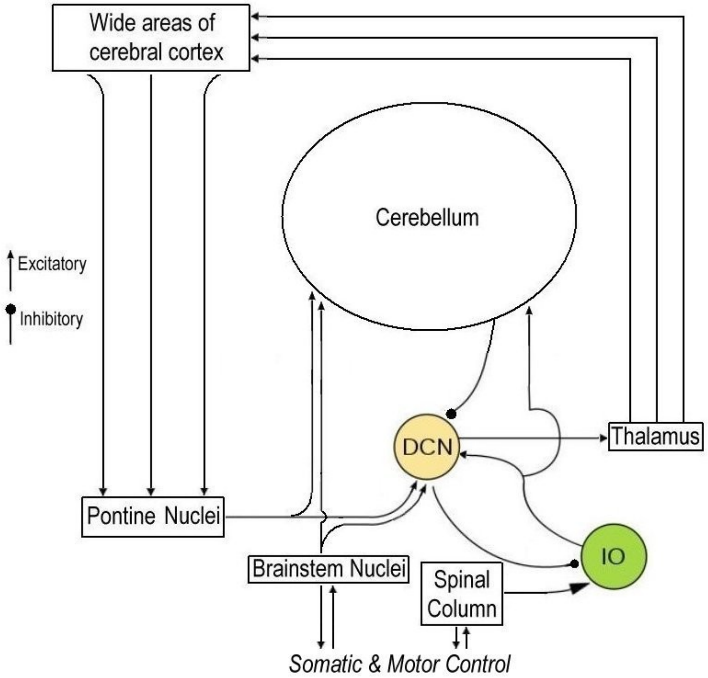




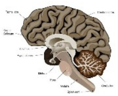
Thalamus receives 98% of sensory input

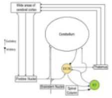
Cerebellum inhibits some signals

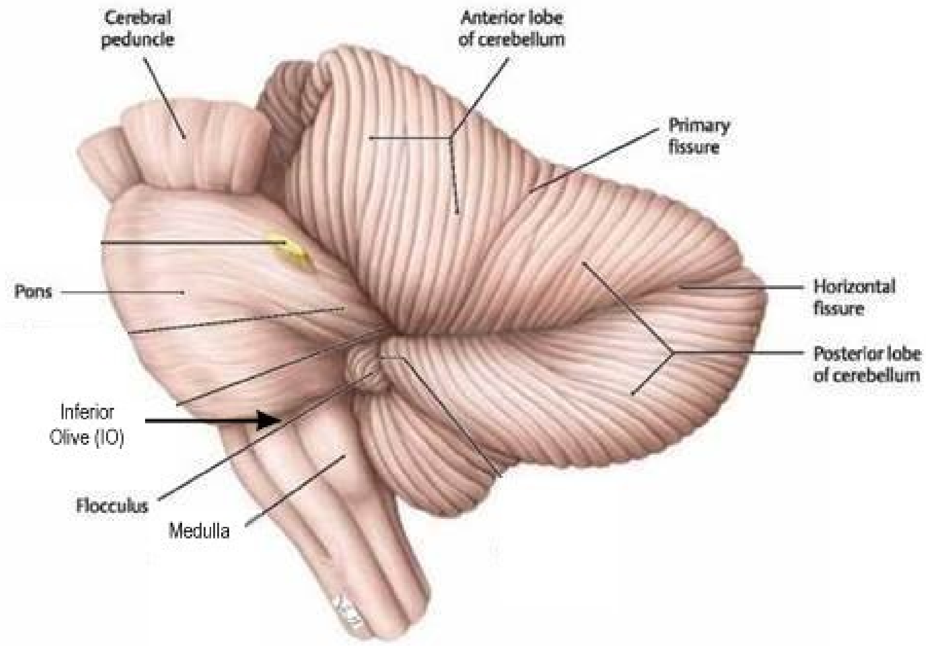


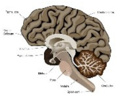
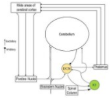


Thalamus receives 98% of sensory input
IO: inferior olive
DCN: deep cerebellar nuclei

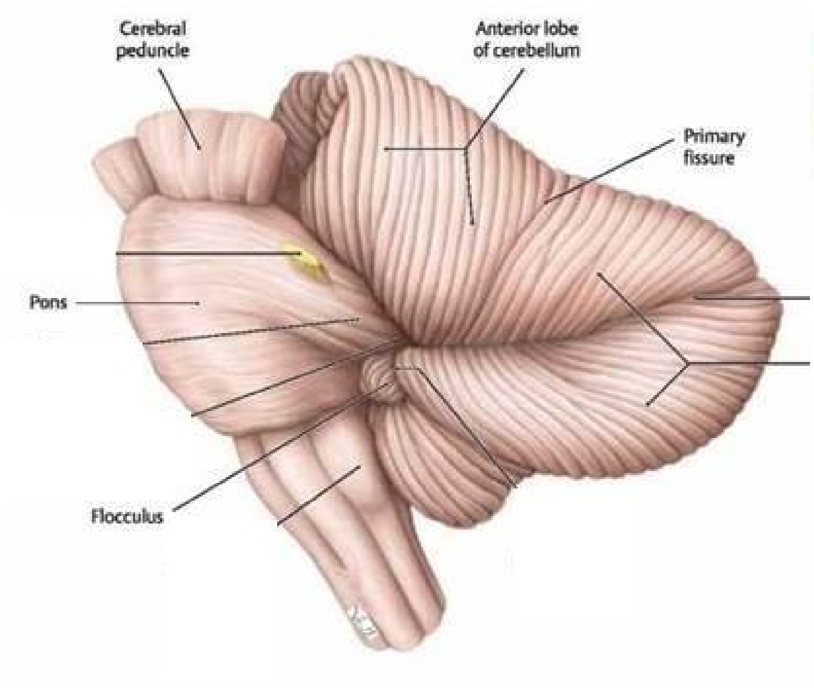


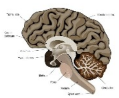


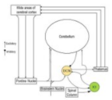

Cerebral peduncle
Anterior lobe of cerebellum
Primary fissure
Pons
Horizontal fissure
Posterior lobe of cerebellum
Inferior Olive (IO)
Flocculus
Medulla

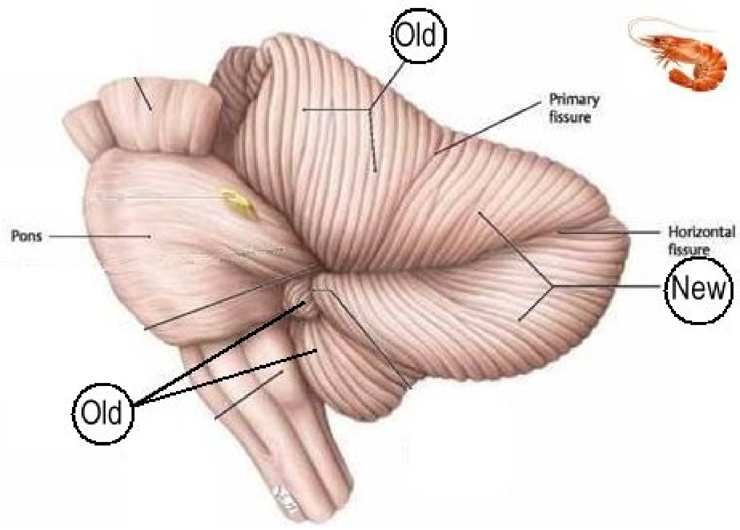
It’s folded

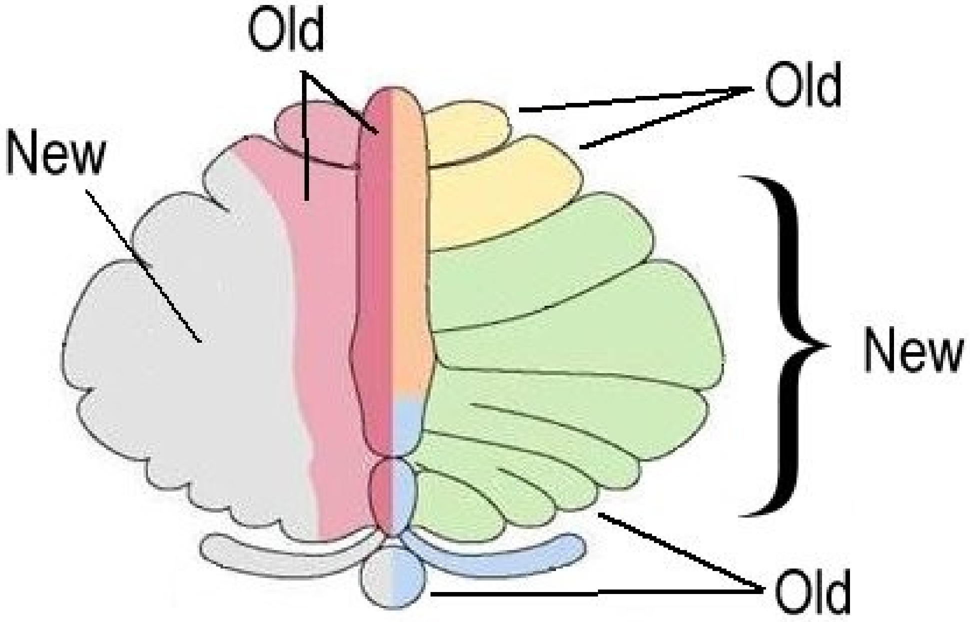

Cerebral
peduncle
Anterior lobe
of cerebellum
Primary
fissure
Pons
Flocculus

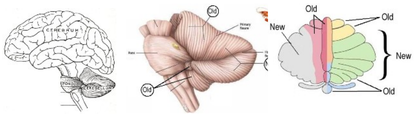




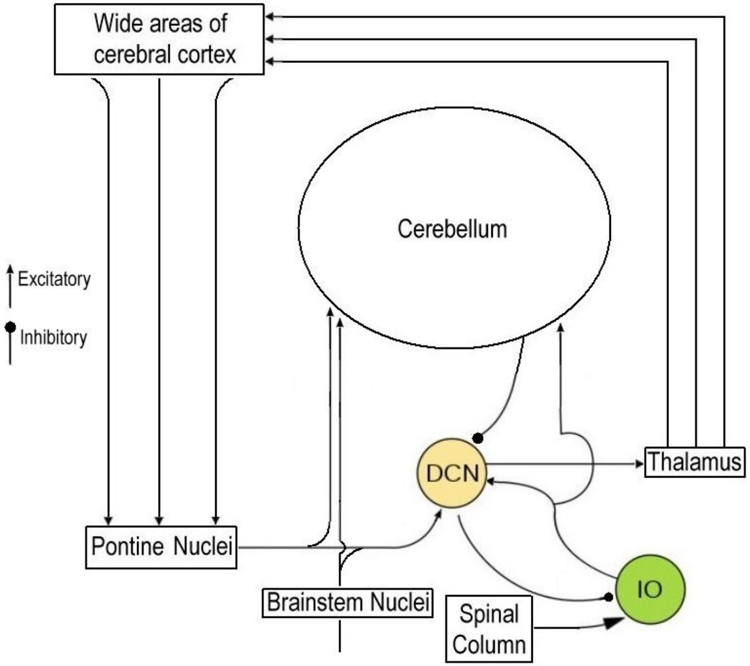
Evolutionary expansions







Motor and cerebral circuits

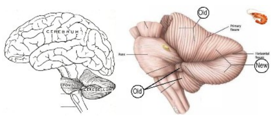


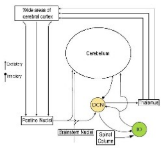
Old:
- Brainstem
- Spinal column
- Some cerebral

New:
- More and more cerebral

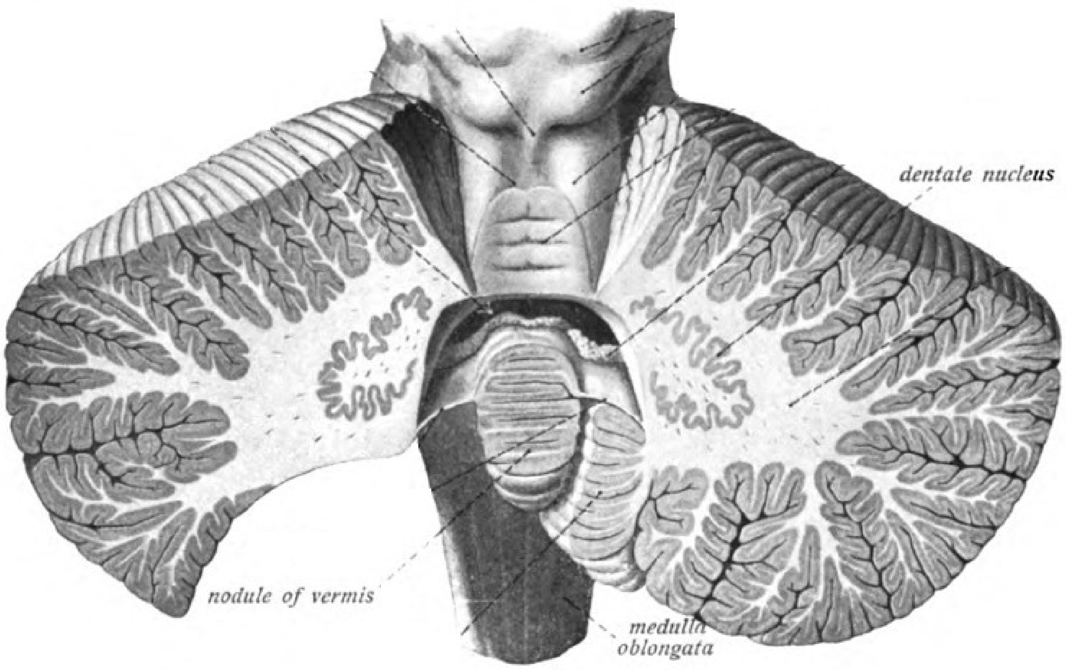
DCN: Deep cerebellar nuclei

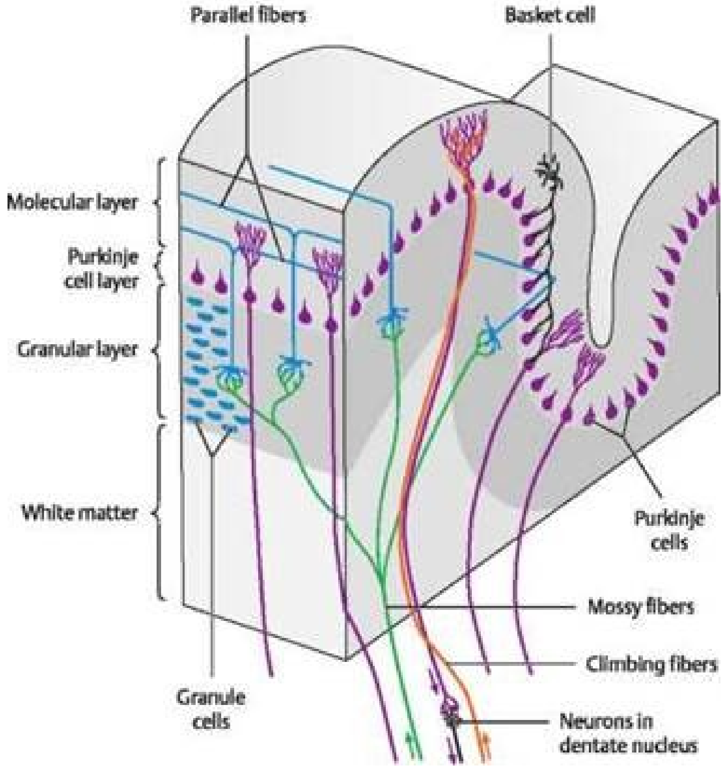
IO: Inferior olive



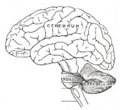


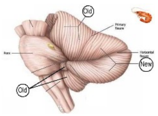
80% of brain’s surface area

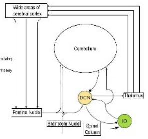


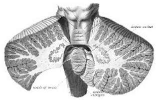


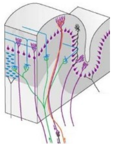
Linked Purkinje cells

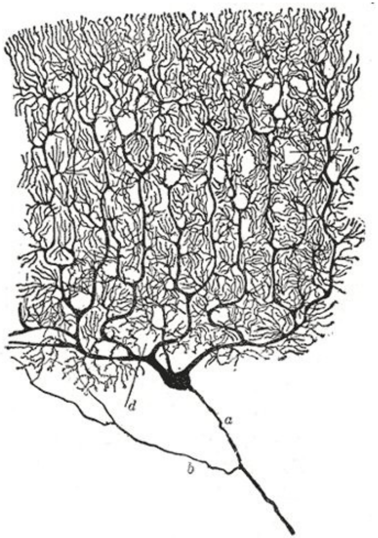


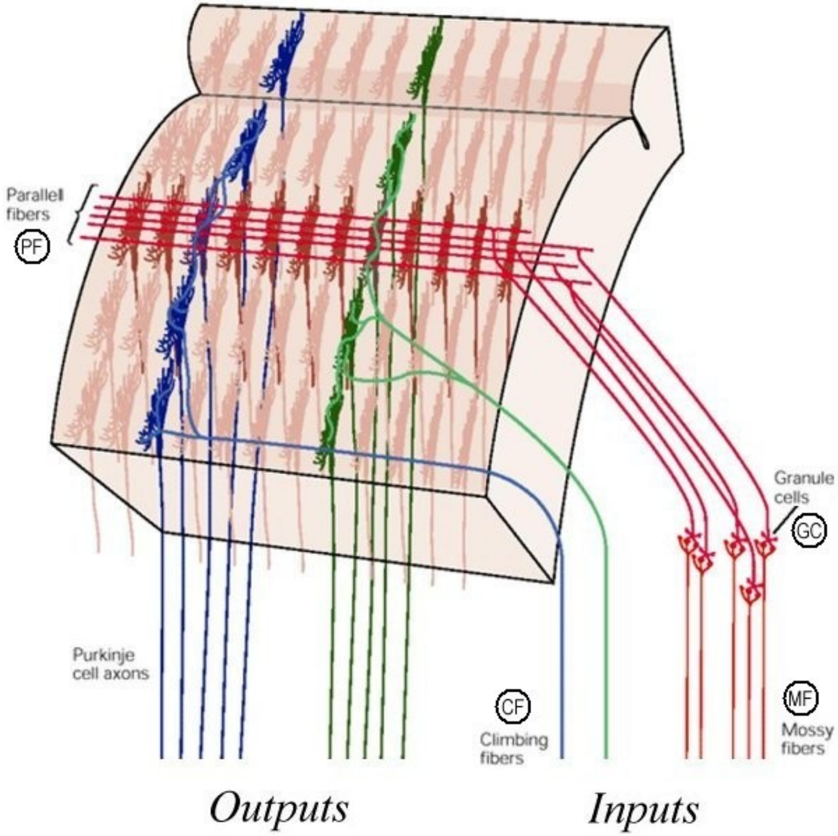




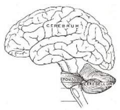
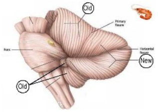
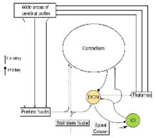
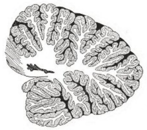


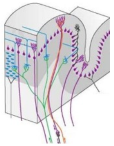






Matrix with stripes

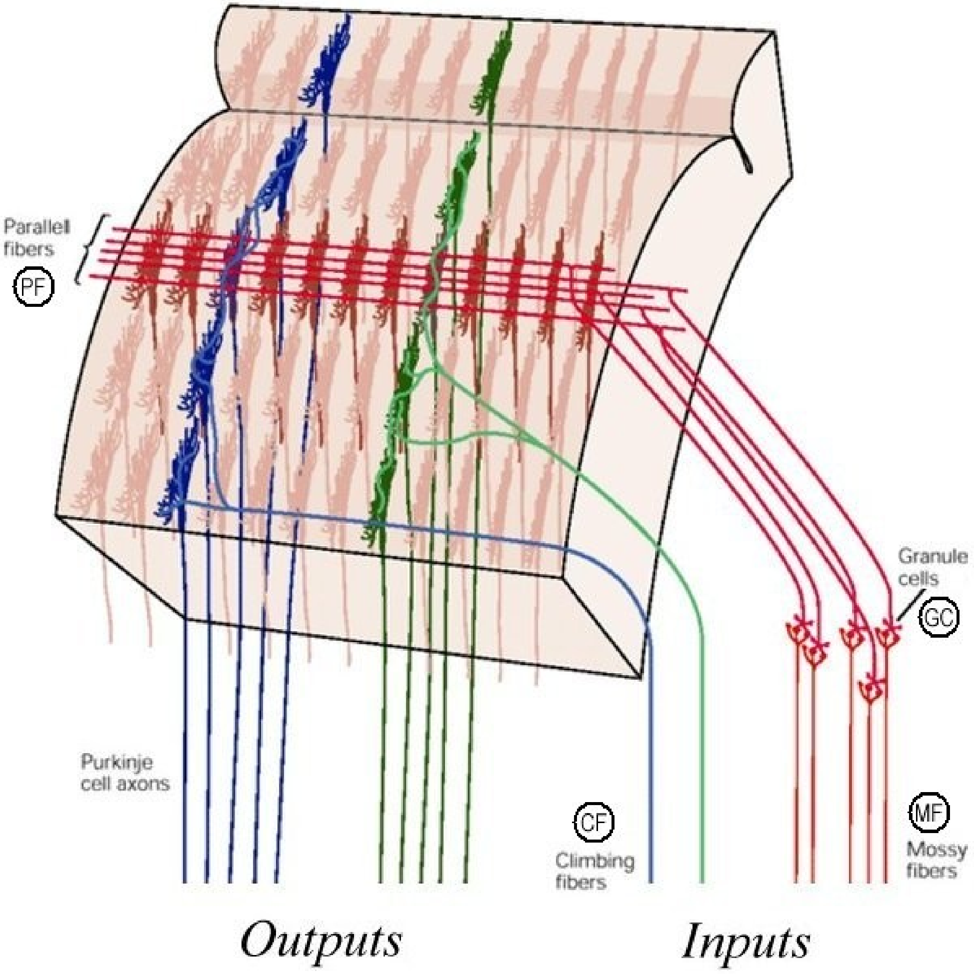


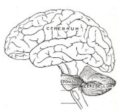
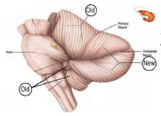
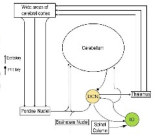
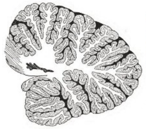
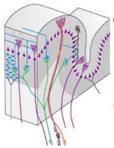
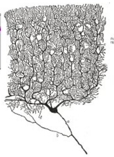
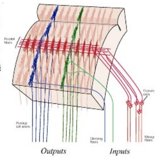
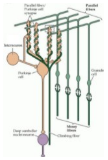
Excitatory inputs to Purkinje cell (PC)

Climbing fibers (CF)
- Entwine branches of dendrite tree.

Parallel fibers (PF)
- Unify each lamina functionally.

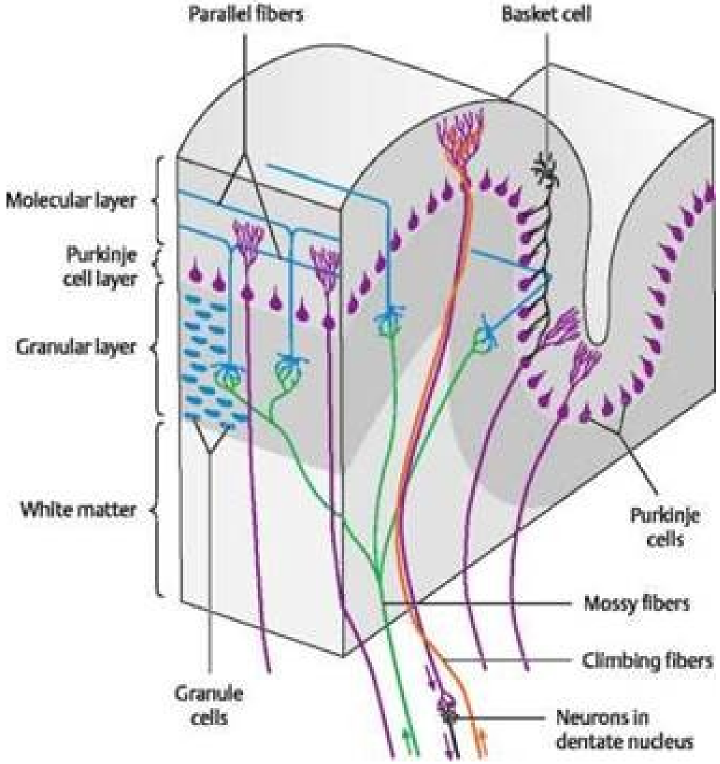
Mossy fibers (MF)
- granule cells (GC) modulate input to PFs.
- Organize ‘stripes’ across laminae.

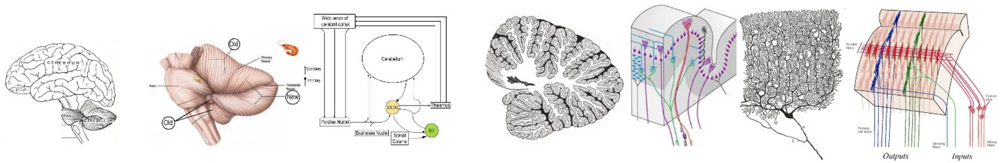


Granule cells (GC)

- Densely packed in the granular layer
- Among smallest in brain
- Most numerous, ~50B
- 75% of brain’s neurons
- ~200 GC/MF, input from 4-5 MFs
- Inhibit MF excitation of PCs

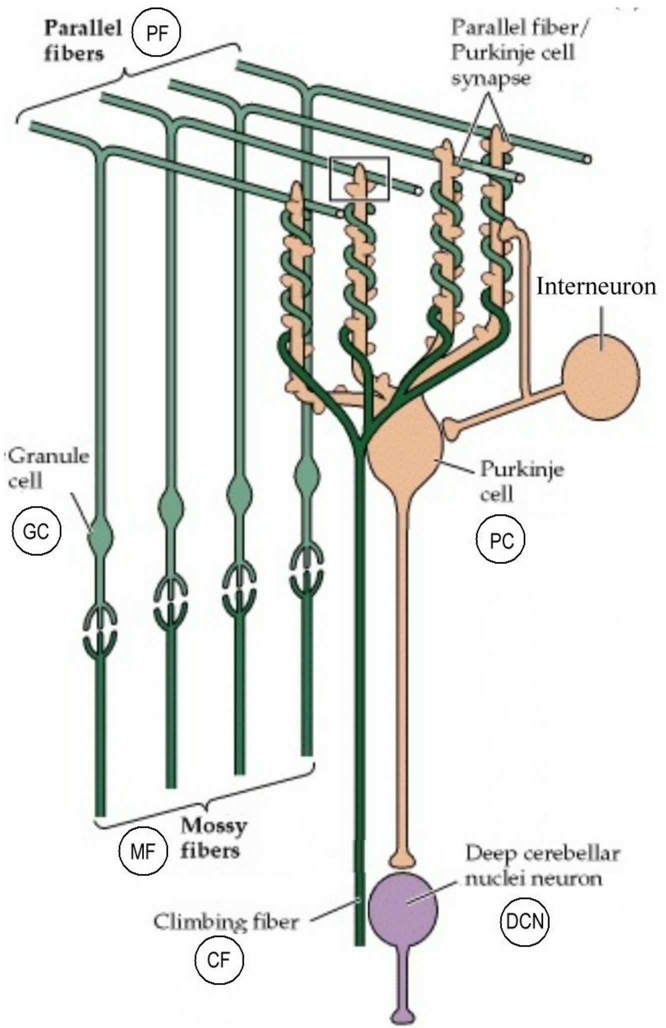


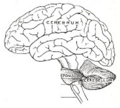
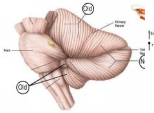
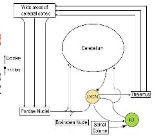
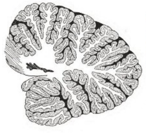
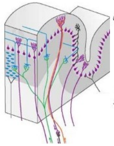


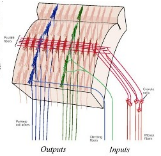
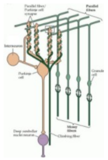
CF Inputs from spinal column & brainstem
- Each CF excites ~30,000 synapses in 1 PC
- ‘Complex spikes’ ~1/s
- Among strongest in the nervous system

PF input from Cerebrum via Pons
- Each PF excites ~150,000 PCs
- ~175,000 PF synapses on each PC
- ‘Simple spikes’ 50-100/s
- PF unmyelinated (ephaptic synchronization)

PC axon
- The only output of cerebellum
- inhibits one neuron in a deep cerebellar nucleus (DCN)

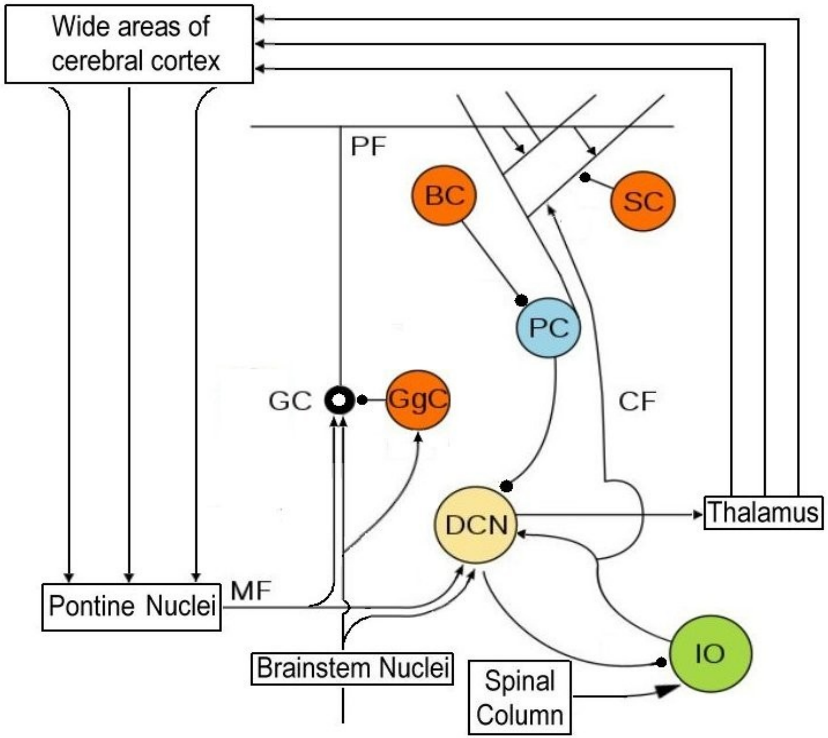


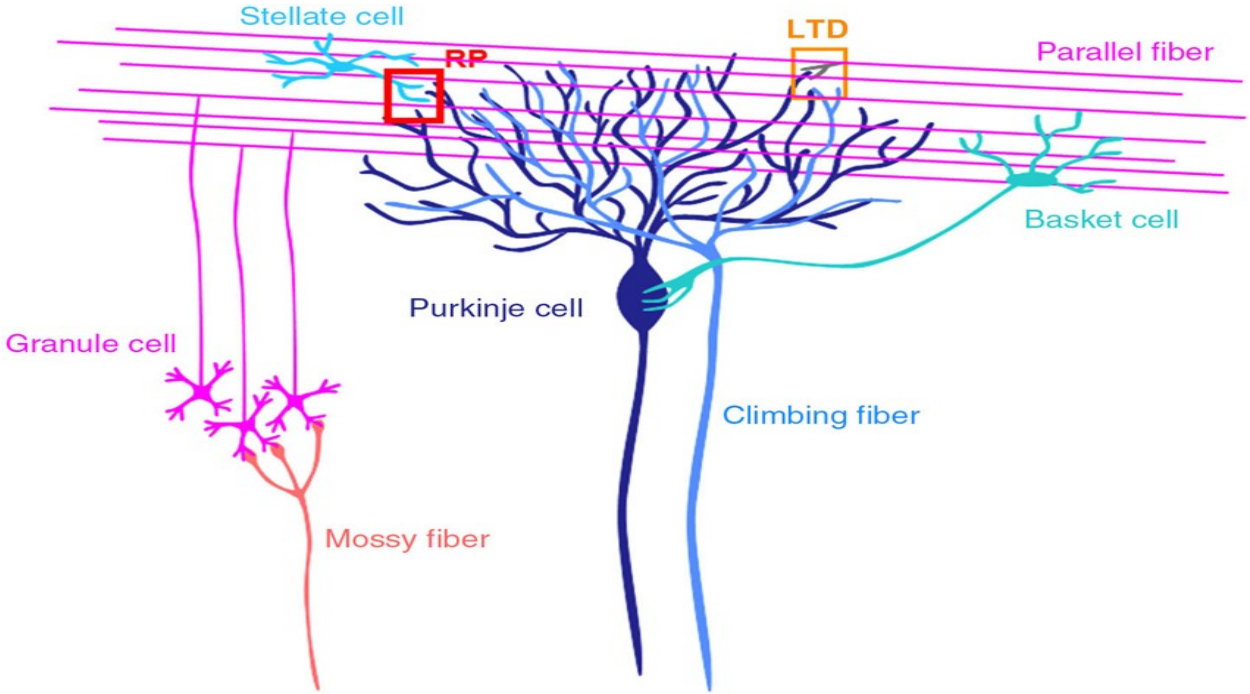



- **Interneurons inhibit specific signals**
  - Inputs from parallel fibers (PF)
  - Basket cells inhibit PC soma
  - Stellate cells inhibit PC dendrite tree
  - Golgi cell: MF & PF inputs, inhibit ~1K GCs

- PC outputs to DCN inhibit specific signals
  - DCN-IO-spine loop
  - DCN-brainstem loop
  - DCN-thalamus-cerebrum-pons loop



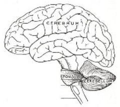
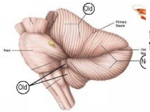
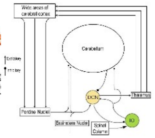
Learning function of interneurons 1

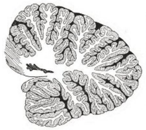
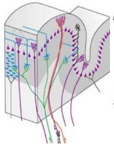
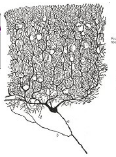
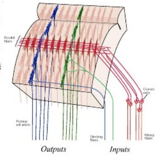


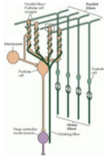
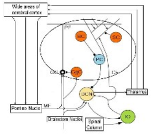
Learning function of interneurons 2

- Long-term depression (LTP) follows from repeated strong activation of parallel fibers (PF) and climbing fibers (CF) together. Purkinje cell synapses become less responsive to (excitatory) glutamate.
- Rebound potentiation (RP) is a long-lasting potentiation of GABAergic (i.e. inhibitory) synaptic transmission induced by postsynaptic depolarization.

The output of a given PC through its axon inhibits a specific neuron in the DCN. Inhibiting a particular Purkinje cell should have the effect of enabling the signal in that connected neuron to continue out of the DCN uninhibited.

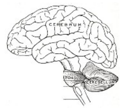
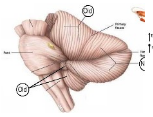
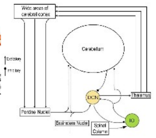
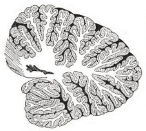
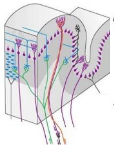
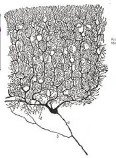
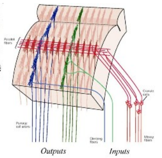



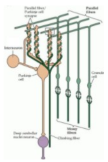
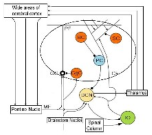
This matrix structure is invariant across the cerebellum.

It serves all functions, motor & cerebral.

The deep cerebellar nuclei (DCN) look like collections of comparators.

What does this matrix structure do?

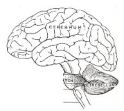
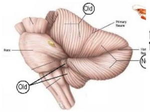
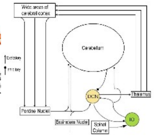
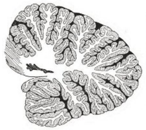
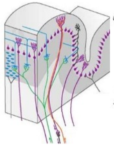
Configuration control (Bill's conjecture)
An input function (my conjecture)

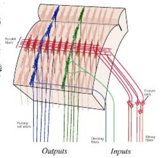
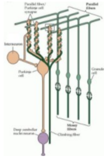
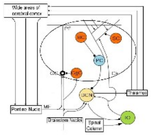
Start with configurations.

- A pattern-recognition system that abstracts *invariant relations* among lower-level signals. (Definition of configurations, *B:CP* p. 122)
- Faster firing = "more of" elbow-bend or head-turn *relation*
- Invariant *relations* even as configuration rotates, translates, etc.

- Therefore, such *transformations* are intrinsic to configuration perception (*B:CP* p. 130 re movie frames is confused).
- Transition: change in *p* at any level is a relationship to remembered value of *p*. Yin (2014) locates motor transition control in the basal ganglia.

Generalized perceptual input function (PIF)

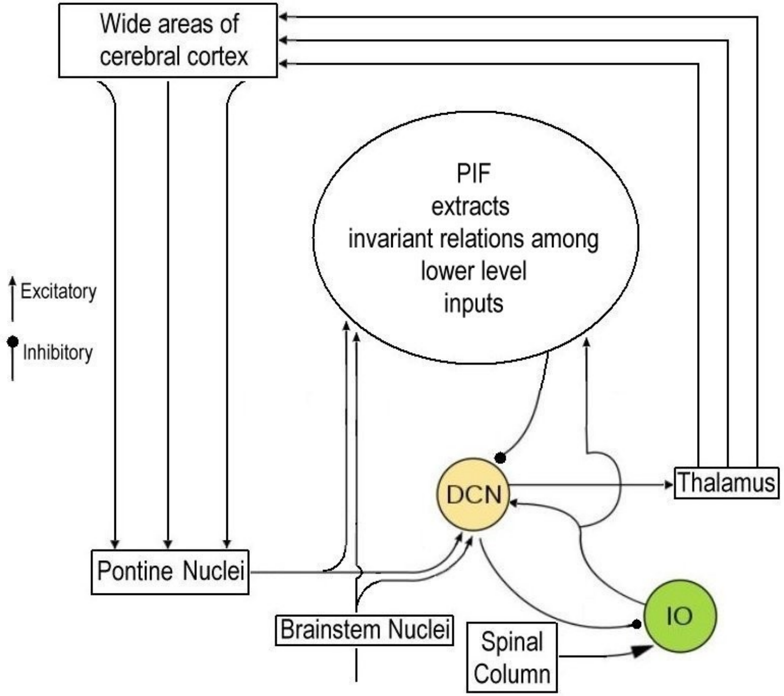




DCN look like collections of comparators

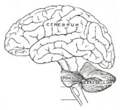
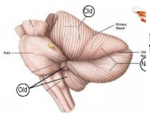
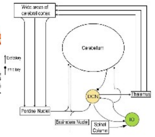
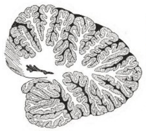
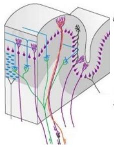
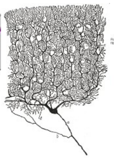
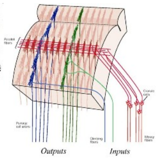
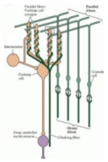
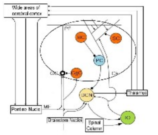
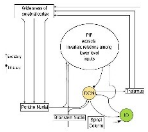
Enter DCN 2x	*Exit Thalamus*
Sensations	→ Configuration
Configurations	→ Relationship
Relationships	→ Category

Imagined configurations, relationships, etc.
→ Abstract configurations, etc.
→ Concepts

Concepts	→ Principles
Principles	→ System concepts



Evolution & development



Evolution

- Corporeal identity
  - kinesthetics, proprioception, control of limbs, orientation, locomotion …
- Configurations in the perceived environment
- Relationships & categories, including social
- Lower levels are inputs for sequences and for planning
- Invariant relations among sequences & among plans (principles)
- Non-physical ‘configurations’ (abstract concepts)

Development

- Accounts for cognitive development after 17-18 months.
- Cerebellum 5% of infant brain, 11% of adult brain