Selected topics in cognitive science and biomodeling

L3: General Organization of Brains

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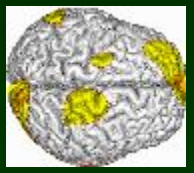
What it is about



1. Core ideas and cybernetic explanations.
2. Basic brain architecture.
3. Information flow in the brain.
4. Examples of communication breakdown.
5. Functions of the brain stem and states of consciousness.
6. Limbic system and emotions.

Core ideas

The brain complexity may be overwhelming but to build interesting systems we need only to understand the principles, core ideas. Engineering (functionalist) perspective:

> Understanding = building a system and checking that its functions approximate what we want sufficiently well.

William R. Klemm, Core Ideas in Neuroscience (2007, e-book) lists 75 "core ideas" or basic principles in neuroscience:

- Cell Biology, Development – more on biological side.
- General ideas, sensory systems, information processing, motor control.
- Emotions, learning & memory.
- States of consciousness – more on psychological physiology side.

We will take similar approach, oriented more towards understanding the flow of information and computer simulations of brain functions.

Cybernetics approach

N. Wiener, ***Cybernetics****, or Control and Communication in the Animal and Machine* (1948): study of the structure of regulatory systems, information flow & control.

Includes control, information and systems theories, focused on self-organization, autonomous systems, and system-environment interaction.

Cybernetics (biocybernetics) overlaps with many other disciplines and only a few research groups use this name.

Bionics (biomimetics): biological inspirations in design of technical systems.

David Marr (1975) viewed information processing systems at 3 levels:

- computational (cybernetic) level: what and why does the system do;
- algorithmic/representational level: how does the system do what it does, what representations/processes are used;
- implementation level: how is the system physically realized; what neural structures and neuronal activities implement functions.

Marr worked mostly on the visual system and memory (hippocampus).

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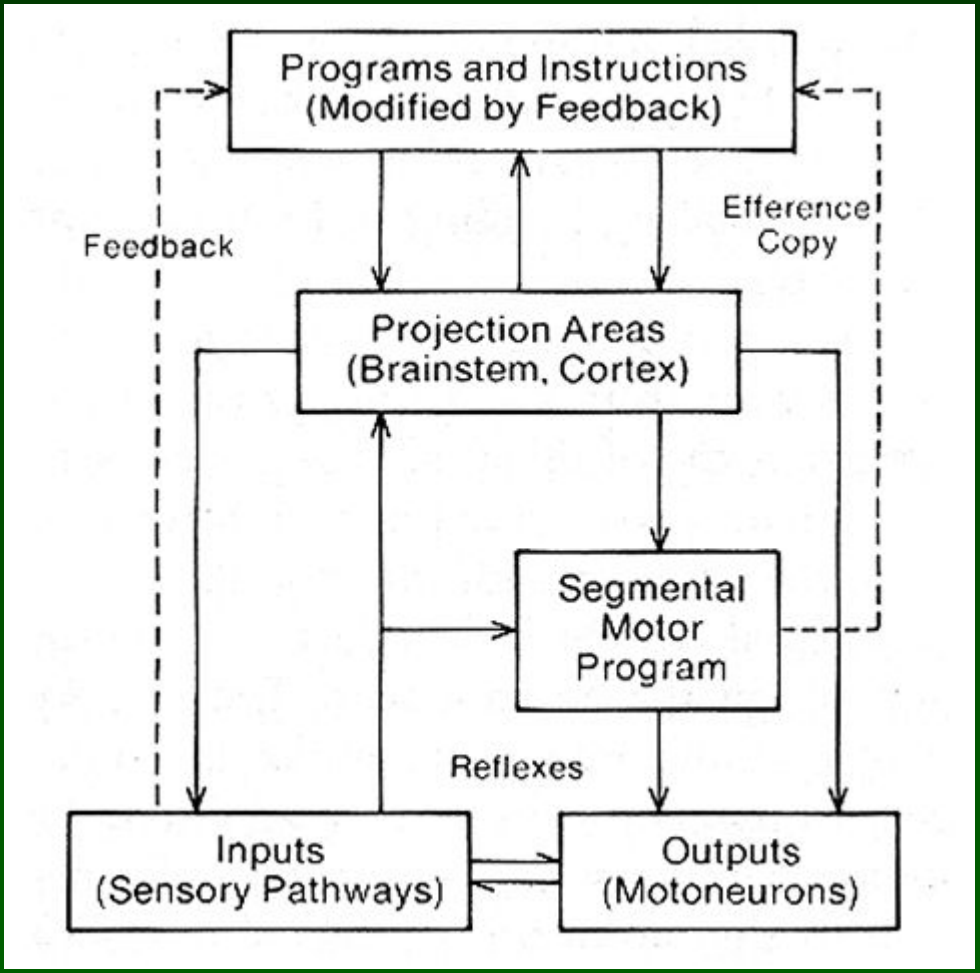
Example: sensorimotor behavior

Action & perception are not separable, perception requires exploration of sensori-motor contingences and affordances (opportunities to act).

Neocortex programs to analyze sensory inputs ask for more information, motor system takes action moving eyes, head, pressing harder, controlling internal information flow.

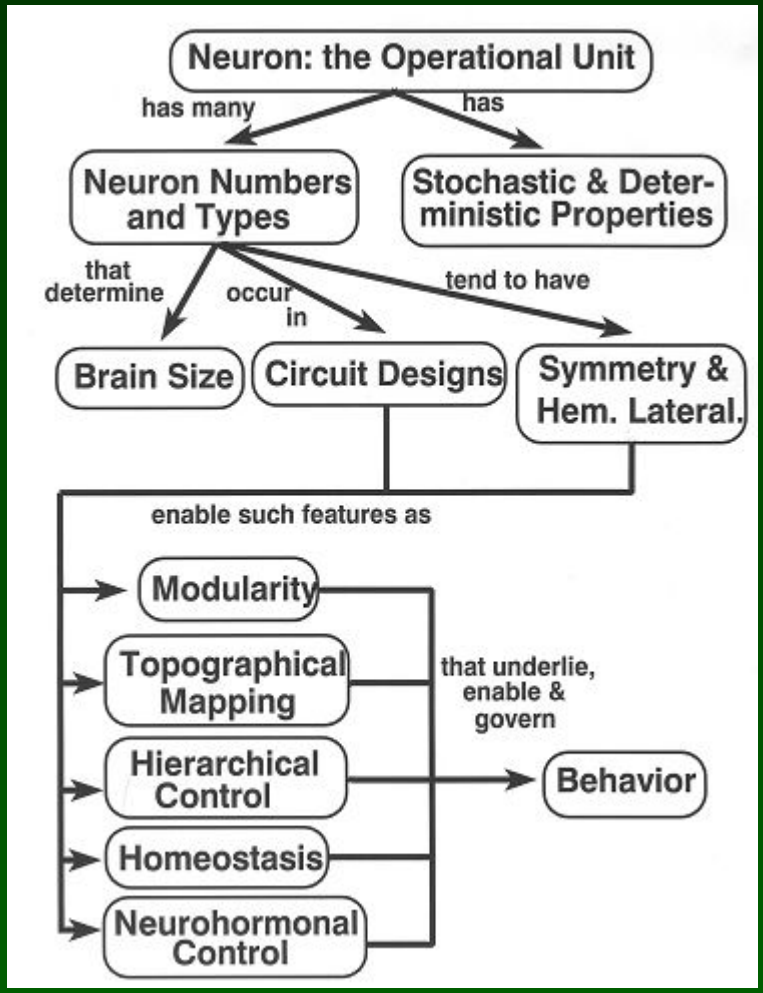
Brain functions are deeply integrated with bodily responses.



General core ideas

After W. Klemm (2007), a bit modified:

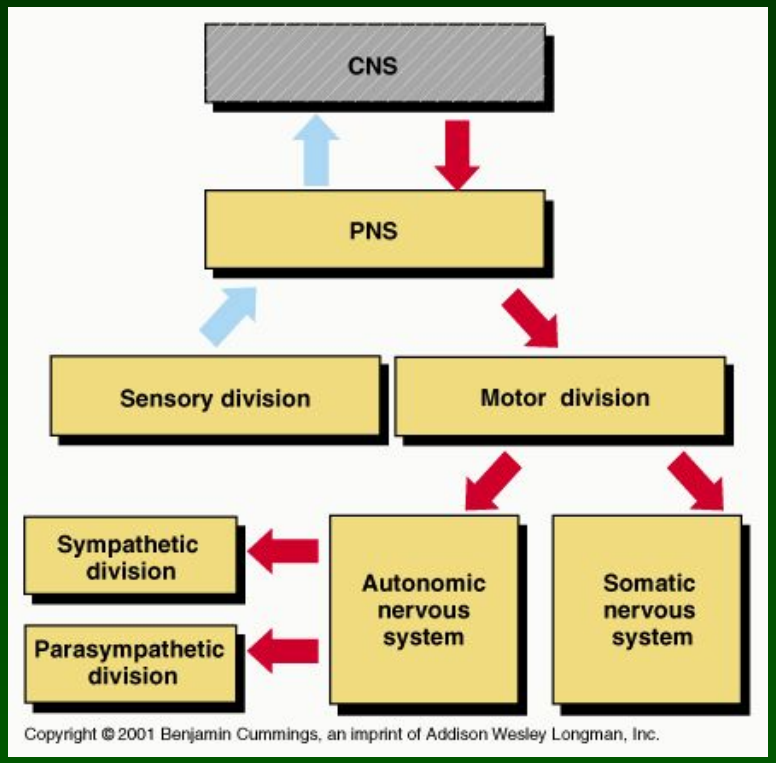
1. neuron doctrine
2. CNS, Central Nervous System, many types of neurons in large numbers
3. neurons form microcuircuits
4. and larger specialized areas
5. that are composed of modules
6. controlled in a hierarchical way
7. using specific mechanisms such as topographical mappings, population coding and associative networks
8. neurons+hormones enable homeostasis
9. controlling behavior.



- It is easier to start top-down, from cybernetic level, and talk about neurons and implementaions of functions later.

General organization

- CNS, Central Nervous System, brain with the spinal cord.
- PNS, Peripherial Nervous System, all nerves and ganglia outside CNS, includes sensory neurons (afferent connections) and the motor neurons (efferent connections) as a part of
- SNS, Somatic Nervous System, and ANS, Autonomic Nervous System.
- *Sympathetic* ANS: arousal in danger, increases heartbeat, blood pressure, adrenaline, "fight or flight".



- *Parasympathetic* ANS does the opposite, "rest and digest" responses.
- *Enteric* ANS controls all aspects of digestion, from the esophagus to the stomach, small intestine and colon, where microbiome resides.

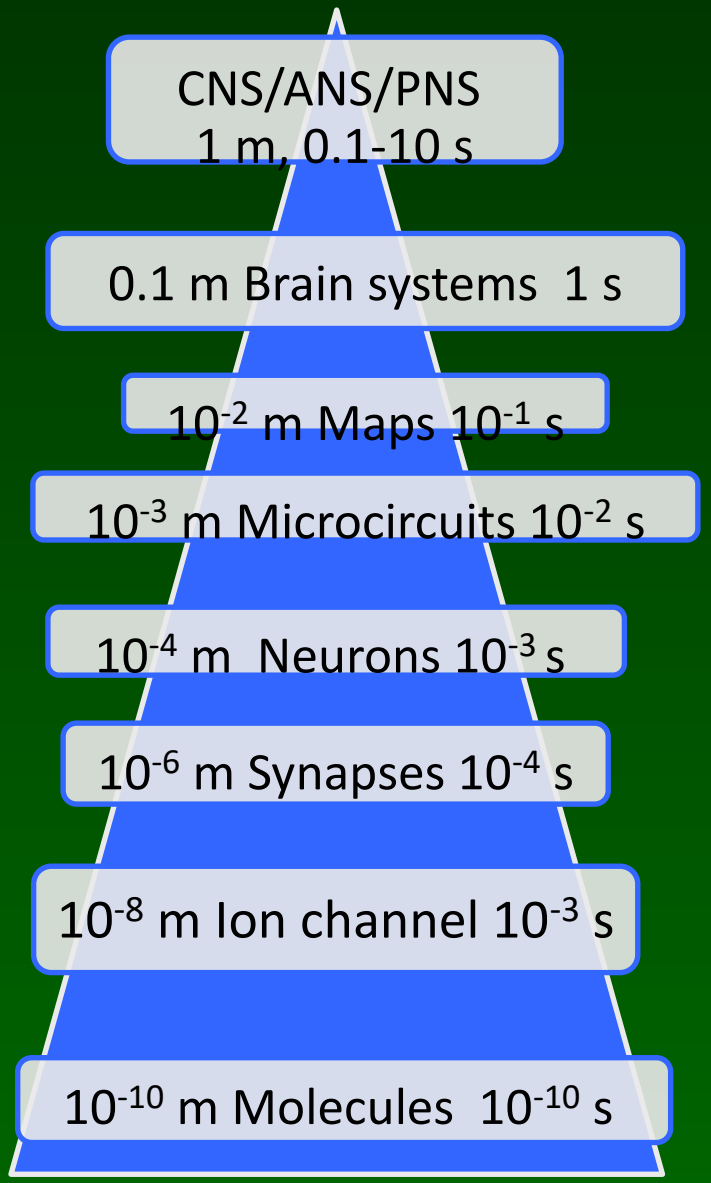
Different views

Spatiotemporal resolution:

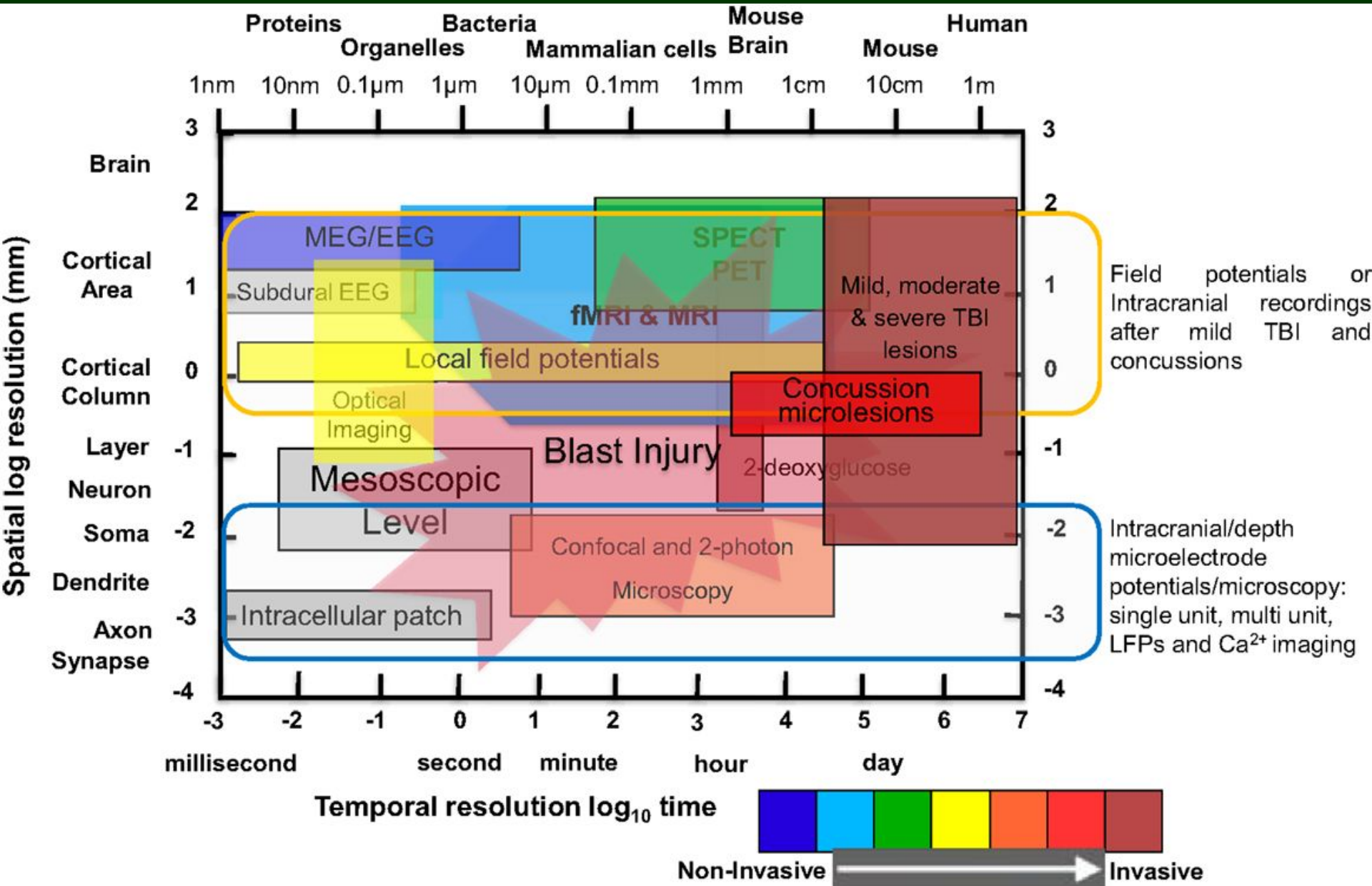
- spatial scale: 10 orders of magnitude, from 10^{-10} m to 1 m.
- temporal scale: 10 or more orders of magnitude, from 10^{-10} s to 1 s.

Architecture:

- hierarchical and modular
- ordered in large scale, chaotic in small;
- specific projections: interacting regions wired to each other;
- diffused: regions interact through hormones and neurotransmitters;
- functional: subnetworks dedicated to specific tasks.



Spatial/temporal resolution of functional neuroimaging techniques (M.K. Jaiswal, 2015)



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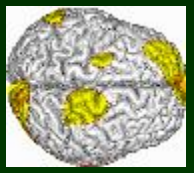

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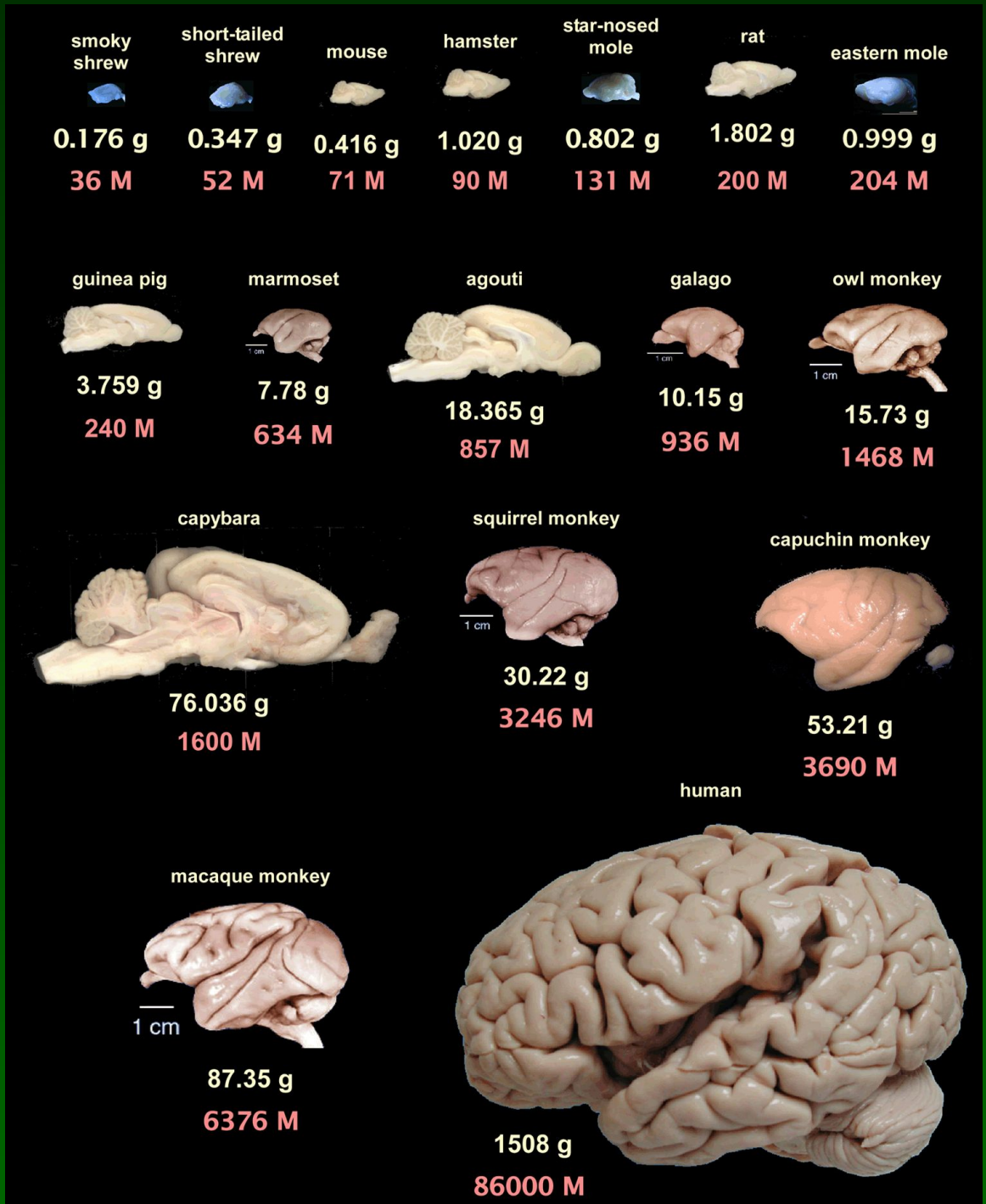
Brains

Brain size matters. More cortex allows for more complex functions.

Mammal brains differs in size by a factor of 100 000!

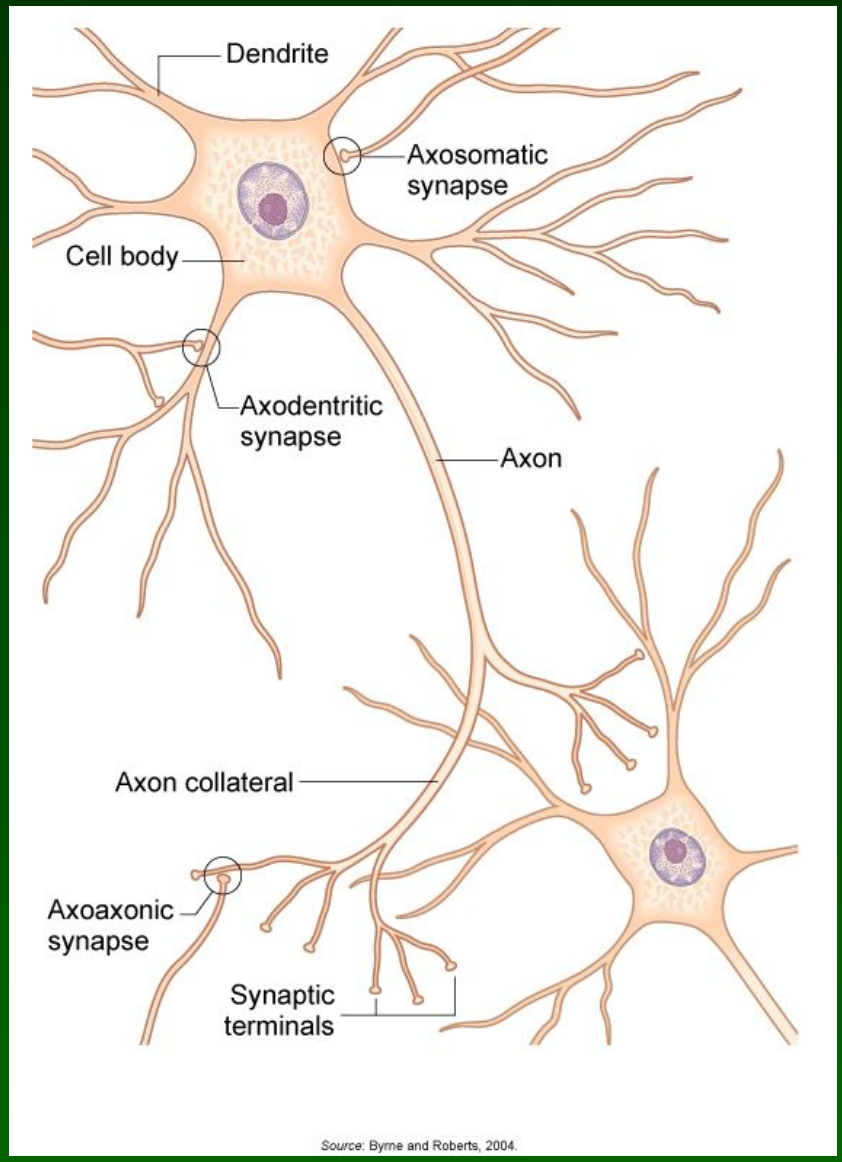
Birds and cephalopods (squid, cuttelfish, octopus) have quite different brain structures but their intelligence is comparable to mammals.

How is that possible?

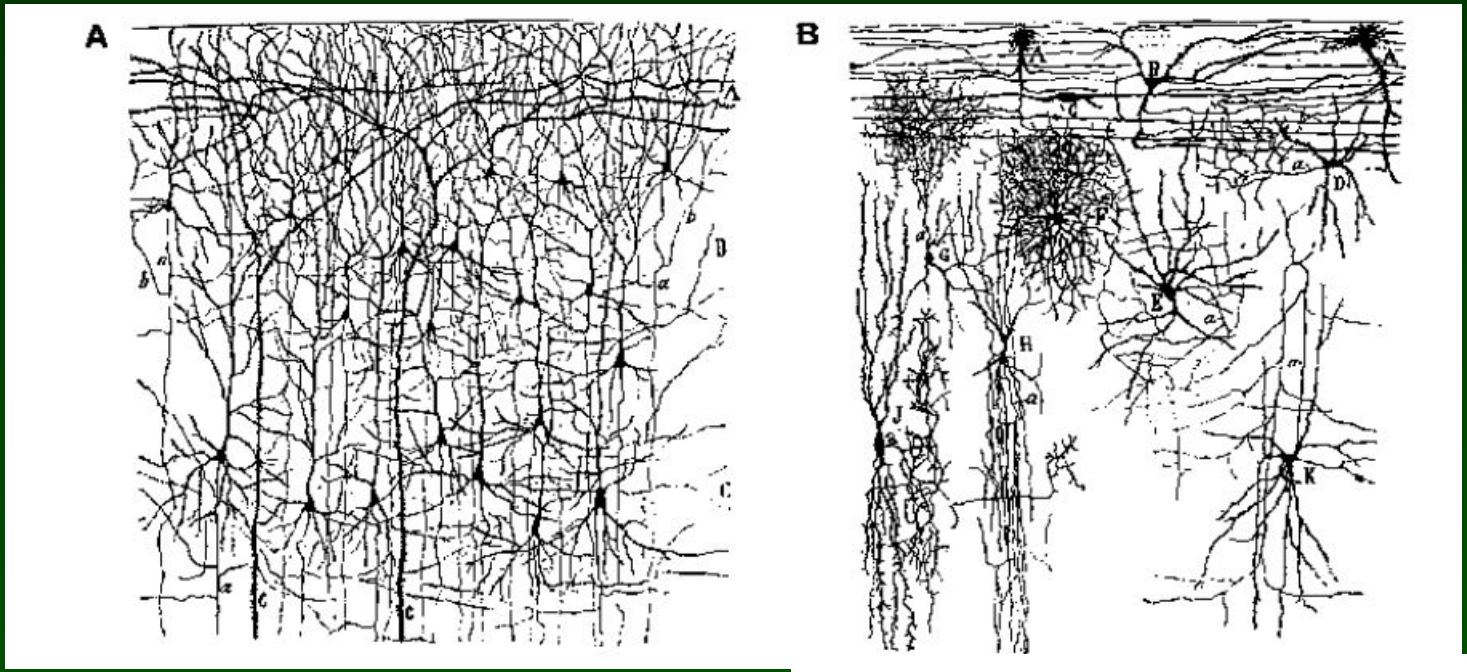


Neurons

- Neurons are specialized cells that may last whole life, unlike other body cells.
- Neurons are connected by excitatory and inhibitory synapses, maintaining low overall activation (2 Hz), only 1% is highly active at given time.
- There are many classes of neurons, neurochemicals, and mechanisms for information processing.
- Many factors determine neuron activity – arousal, sleep-waking cycle, emotions, availability of glucose and oxygen, vairious neurochemicals.
- Networks of neurons can rapidly adapt their activity (network states), slower neuroplastic processes change physical connection structure.



Inhibitory and excitatory neurons

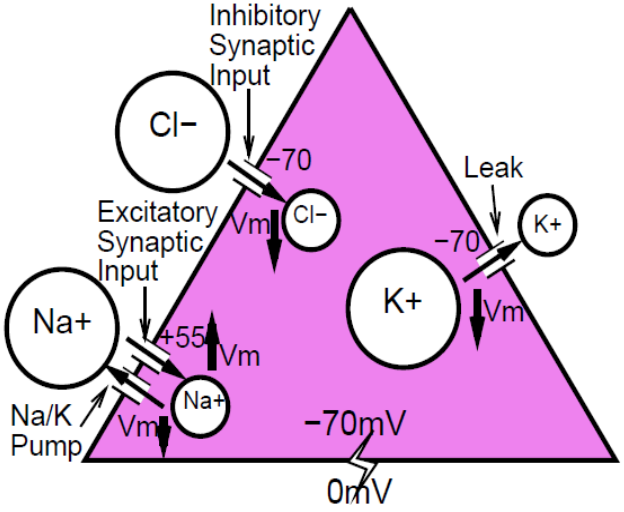


Action potential (spike): sum all local potentials in space/time windows.

Large number of ion channel types exist.

Glutamate controls Na^+ channels, contributing to excitation.

GABA controls flow of Cl^- ions inhibiting activations.

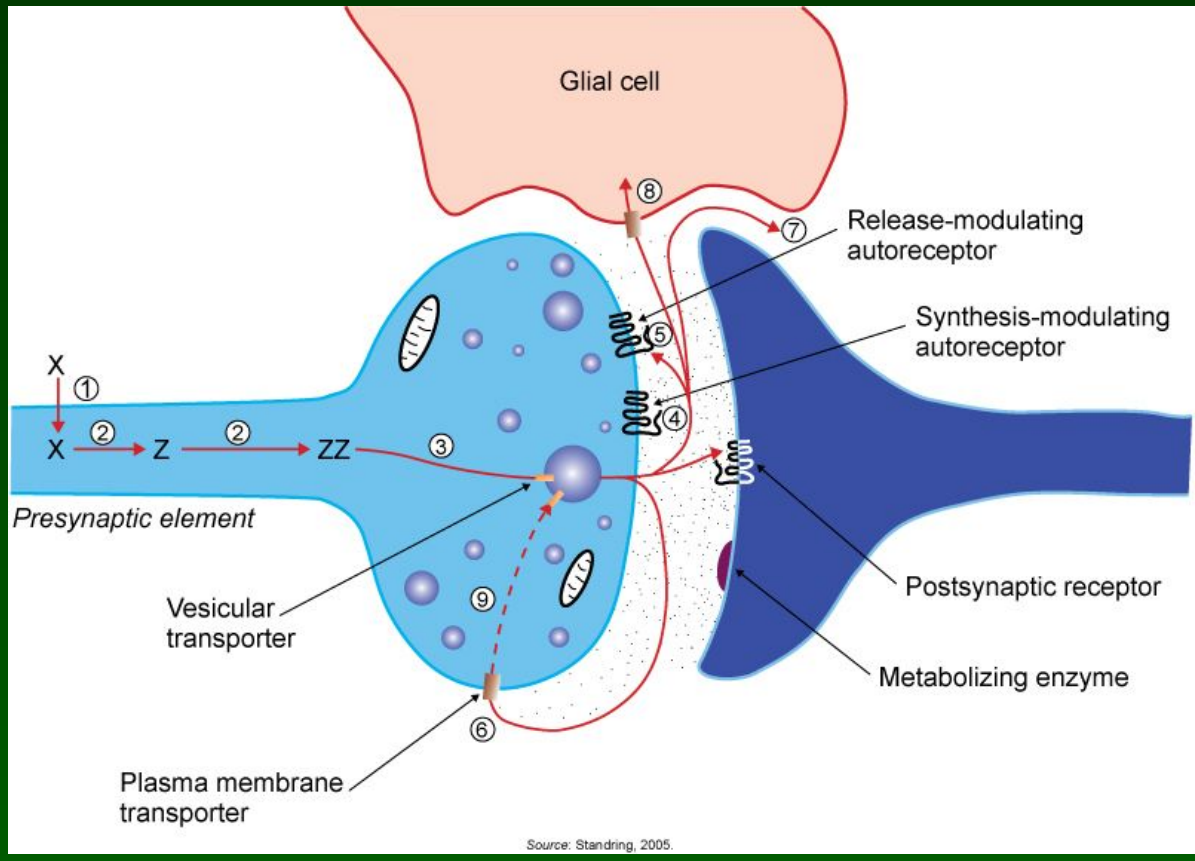


Synapses

A spike in the presynaptic cell triggers release of neurotransmitter that diffuses across the synaptic gap and changes potential of postsynaptic cell.

Efficiency of signal transmission corresponds to synaptic weights in network of neurons.

Some neurotransmitters are produced in terminal axon boutons holding many vesicles.



Chemical communication is a very early evolutionary invention to coordinate movement in multicellular organisms.

4 neurotransmitters

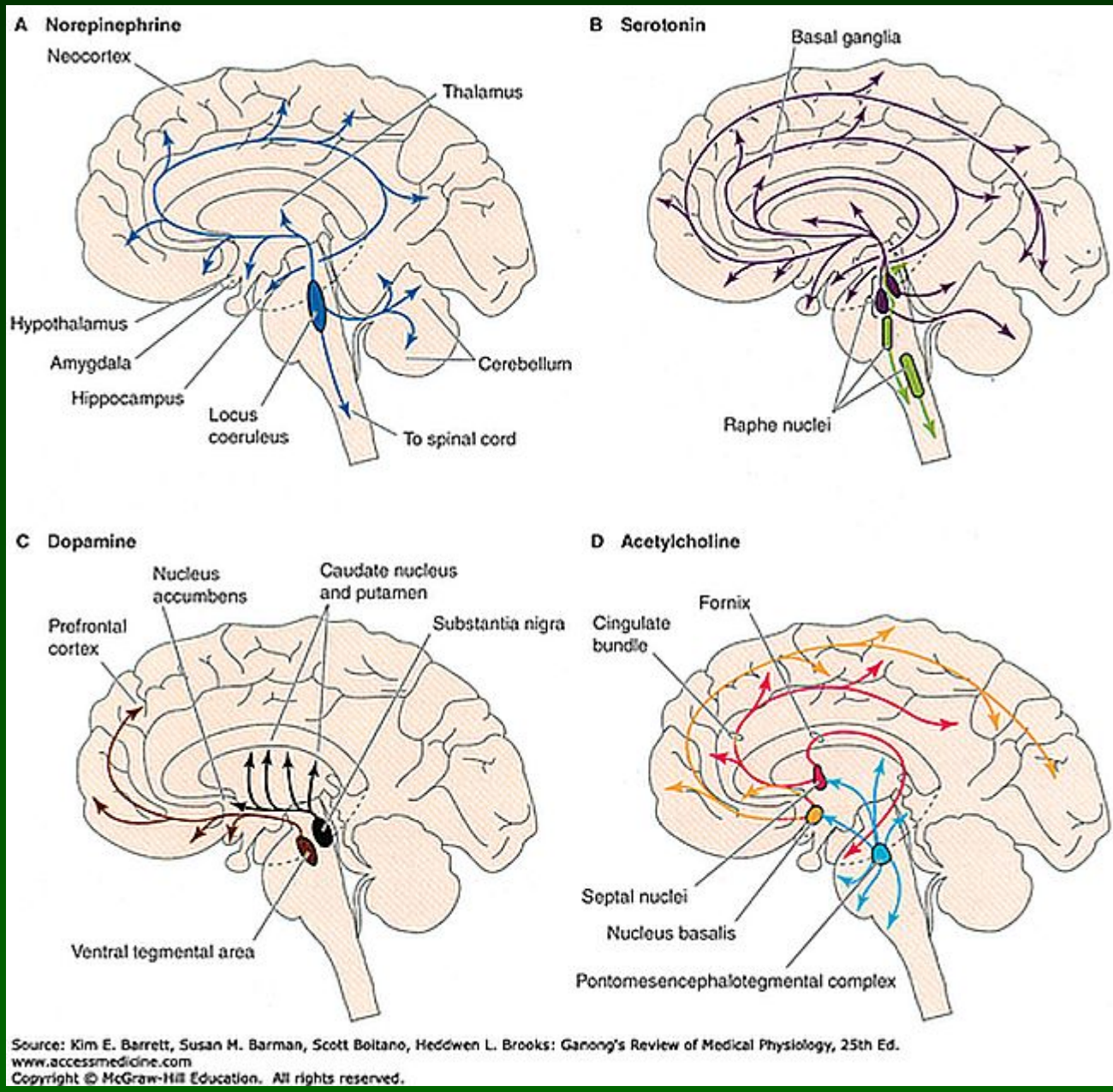
Norephinephrine (noradrenaline) – alertnes, attention.

Serotonin – mood, depression.

Dopamine – reward, motivation, movement

Acetylocholine – memory, learning.

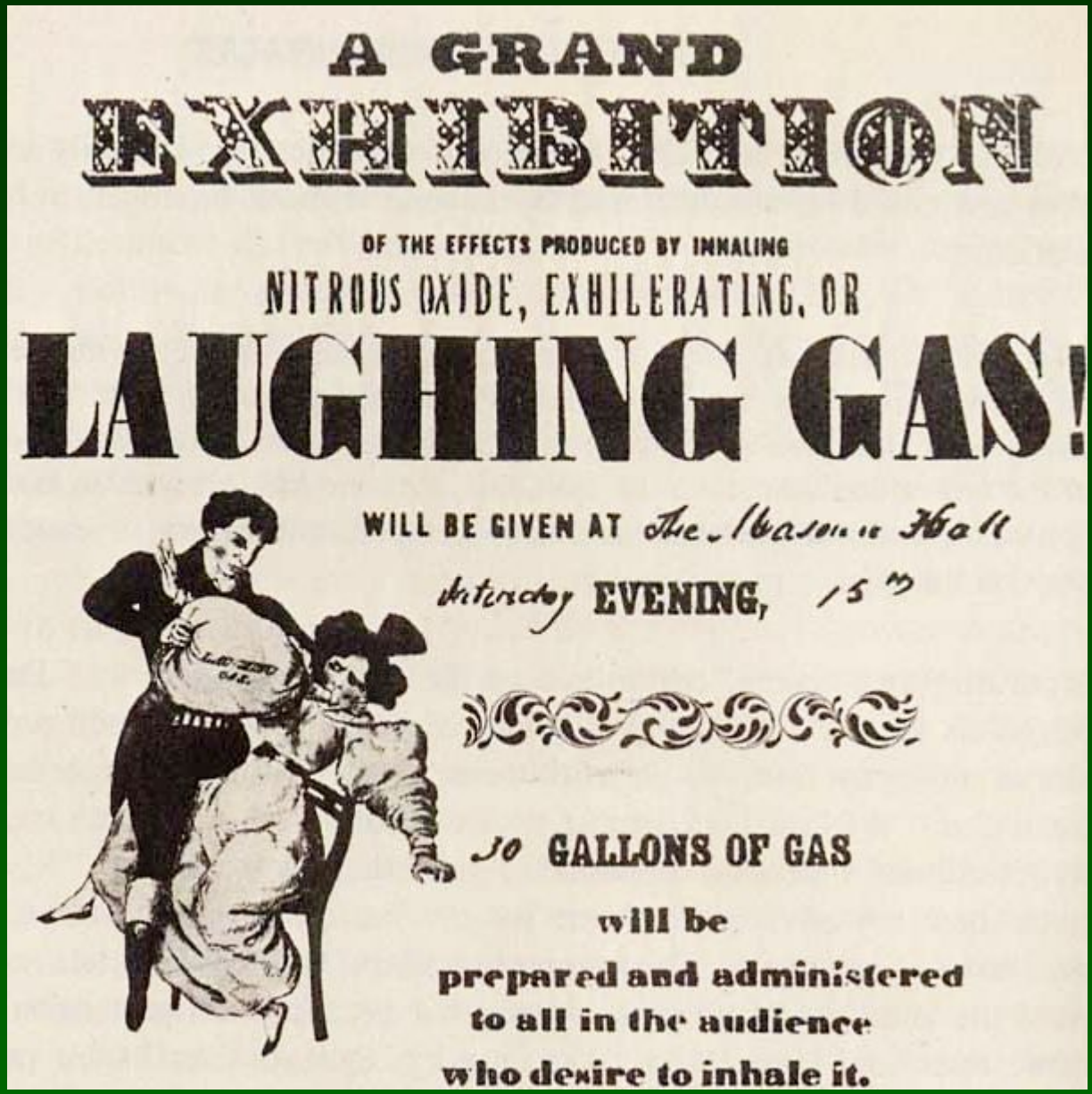
Histamine has 23 physiological functions.



Effects of small molecules

Psychoactive substances are usually found in small quantities in the brain itself: laughing gas nitrous oxide N_2O, endorphins, anandamide.

"The gas will be administered only to gentlemen of the first respectability. The object is to make the entertainment in every respect a genteel affair".



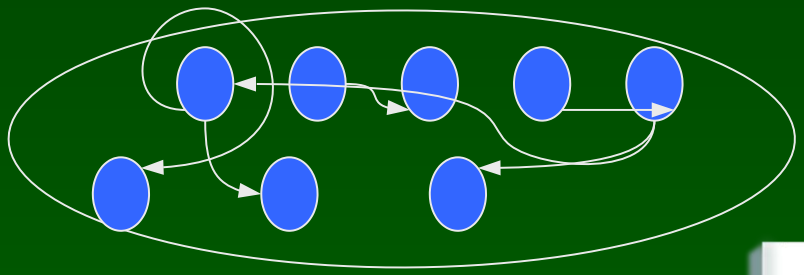
Isocortex has uniform structure

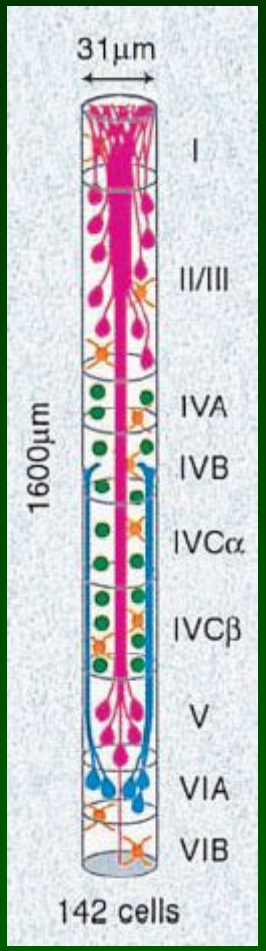
V. Mountcastle argued that all regions of the brain perform the same kind of computations.

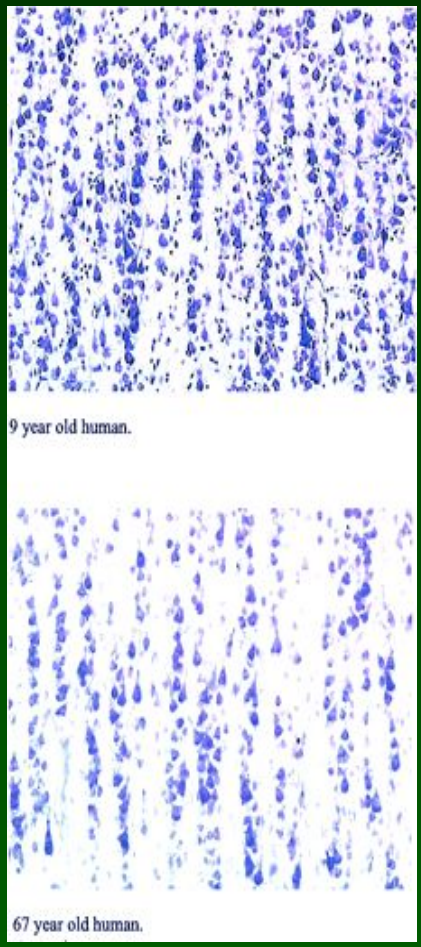
Groups of neurons (minicolumns) are connected in a pseudorandom way.

Minicolumns organized in macrocolumns

VB Mountcastle, Special issue of *Cerebral Cortex* on columns. *Cerebral Cortex* **13**, 2003

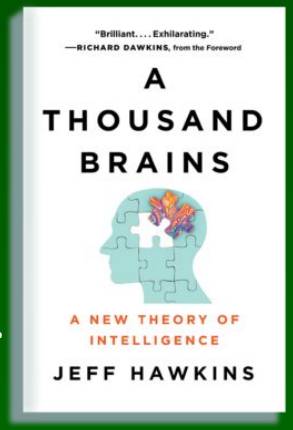






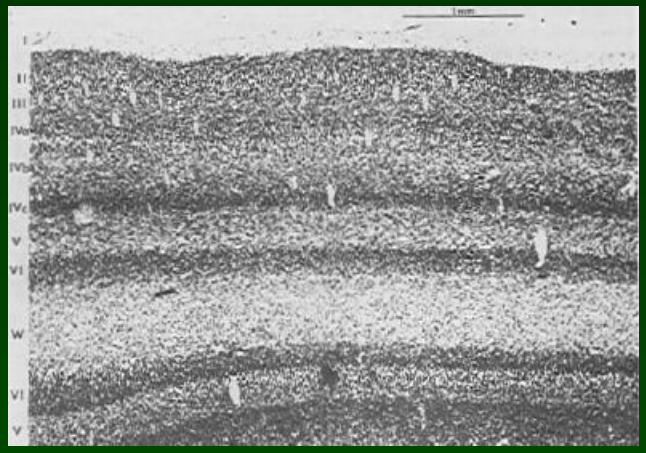
We'll never have true AI without first understanding the brain.

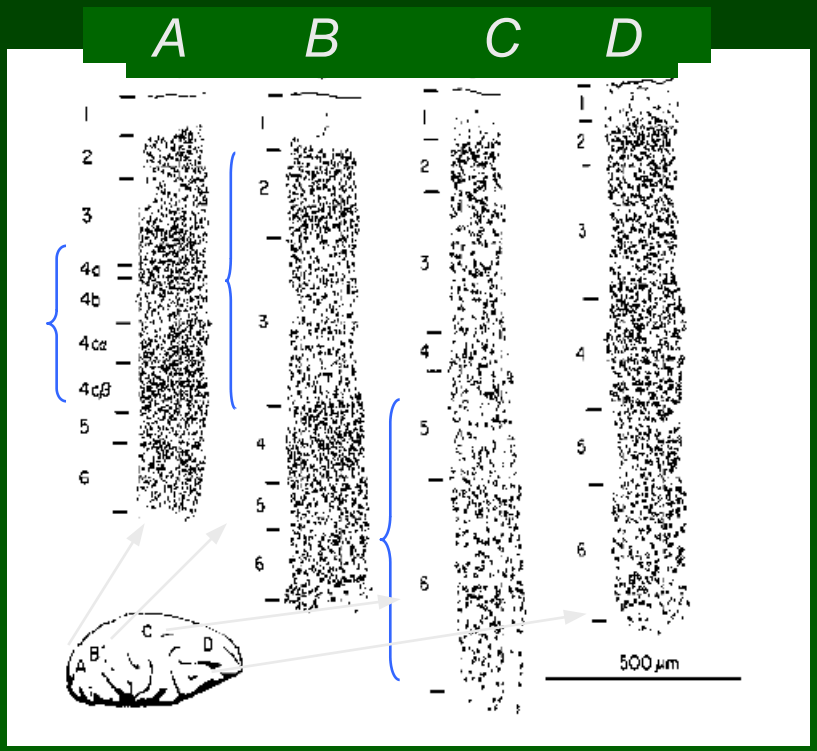
Jeff Hawkins (2020).



Laminar structure

The cortex has a thickness of 1.5-4 mm and consists of 6 layers, with different thicknesses in different parts of the brain.





A - the visual cortex has a thicker input layer 4a-c;

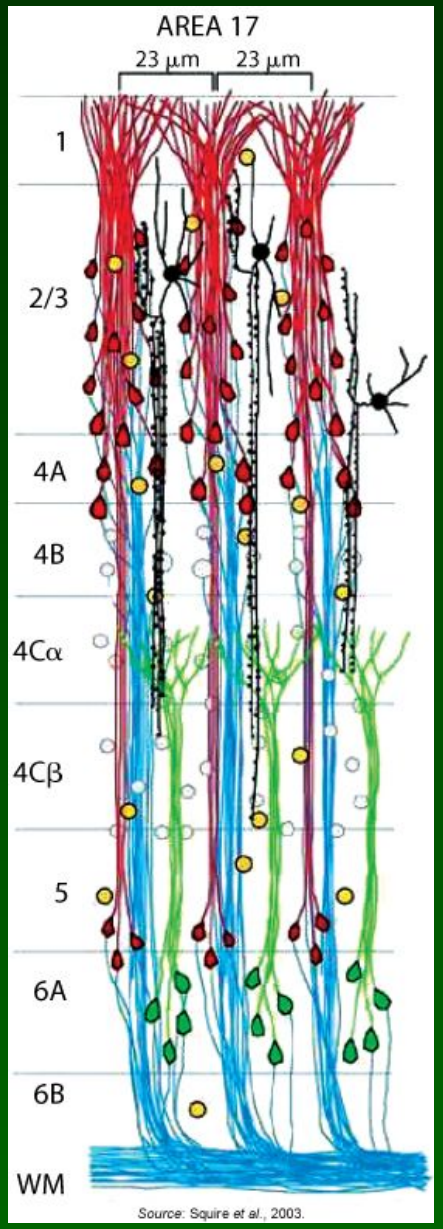
B - the parietal cortex has thicker hidden layers 2 and 3;

C - the motor cortex has thicker output layers 5-6;

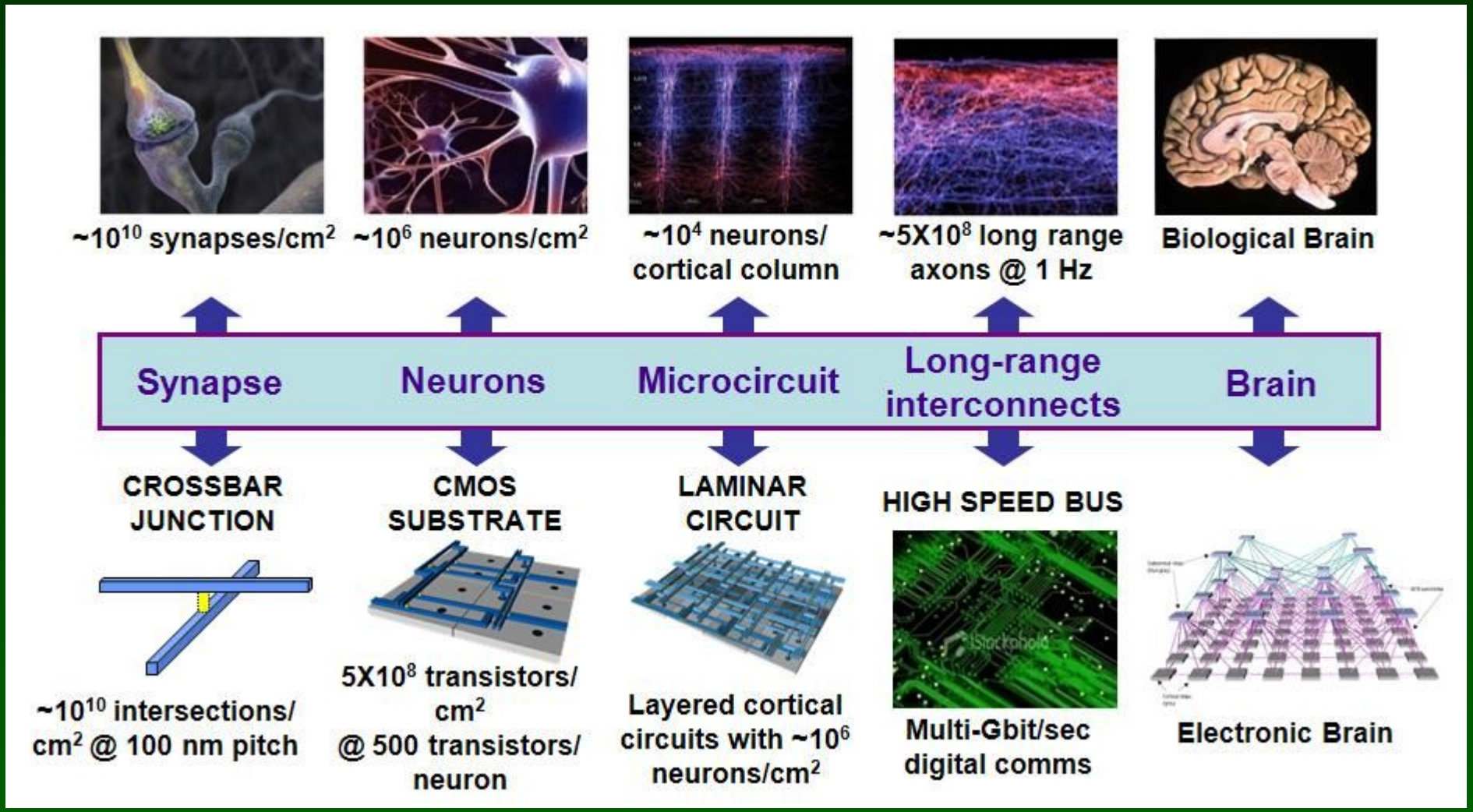
D – the prefrontal cortex doesn't have markedly thicker layers.

Structure of the cortex

- The neocortex has six major layers organized in cortical columns.
- Older subcortical nuclei have paleocortex structure with 3 layers, and oldest archicortex (ex. olfactory cortex, fish or amphibian brain) has 3-4 layers.
- Layer I consists mostly of dendrites (input fibers).
- Minicolumns may have 100 neurons and be clustered into hypercolumns with 30 000 neurons.
- Neurons in cortex grow, migrate, connect, disconnect, create microcircuits, and die changing topology of the whole network and function.
- Structure on the microscale is chaotic, on the large scale similar to other brains in the same species.
- This image is based on fragment of V1 visual cortex, below cortex long axons with matter are seen.



Can we build cortex?



Source: DARPA Synapse project. Neuromorphic computing is finally coming!