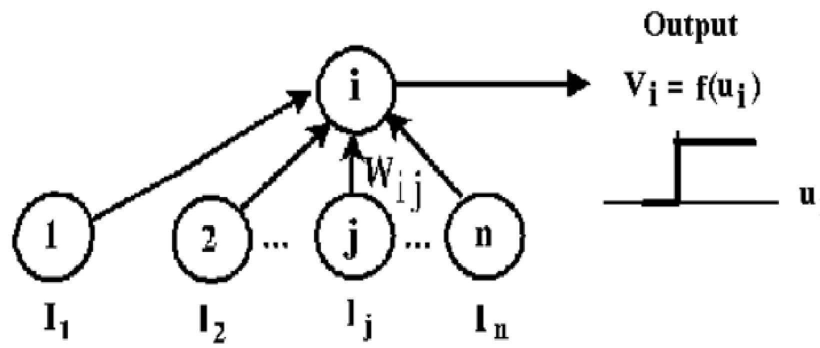
CmpE 489/COGS 500: Cognitive Science
Week 4

Computational Models of Neurons
Representation of Sensory Information
Multisensory integration in cortex

Adapted from Albert Ali Salah's slides

Rosenblatt's simple perceptron

- The weights and thresholds were not all identical.
- Weights can be positive or negative.
- There is no absolute inhibitory synapse.
- Although the neurons were still two-state, the output function f(u) goes from [-1,1], not [0,1].
- Most importantly, there was a learning rule.



$$V_i = f(u_i) = \begin{cases} 0 & : \quad u_i < 0 \\ 1 & : \quad u_i \geq 0 \end{cases}$$

$$u_i = \sum_j W_{ij} I_j + \theta_i$$

http://ecee.colorado.edu/~ecen4831/lectures/NNet2.html

Learning with the perceptron

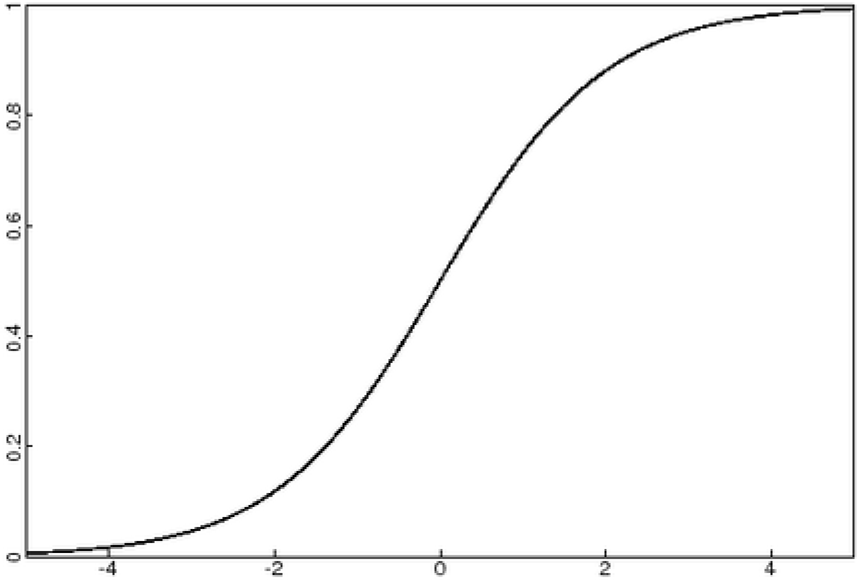
- $T = \{(\mathbf{x}_1, y_1), \ldots (\mathbf{x}_n, y_n)\}$ is a training set of n pairs of input $\mathbf{x}_i$ and desired output y_i
- To learn the correct weights **w**:
  - Initialize **w** randomly
  - For each sample j do:
    - Calculate the actual output $y'_j = \mathbf{w}\mathbf{x}_j$
    - Adapt the weights $\mathbf{w}_k' = \mathbf{w}_k + \alpha(y_j - y_j')\mathbf{x}_{jk}$ for each $\mathbf{w}_k$
  - Repeat until the error is sufficiently small

Other considerations

- Bias term: w_0
- Adding nonlinearity:
  - Logistic function
  - Hyperbolic tangent

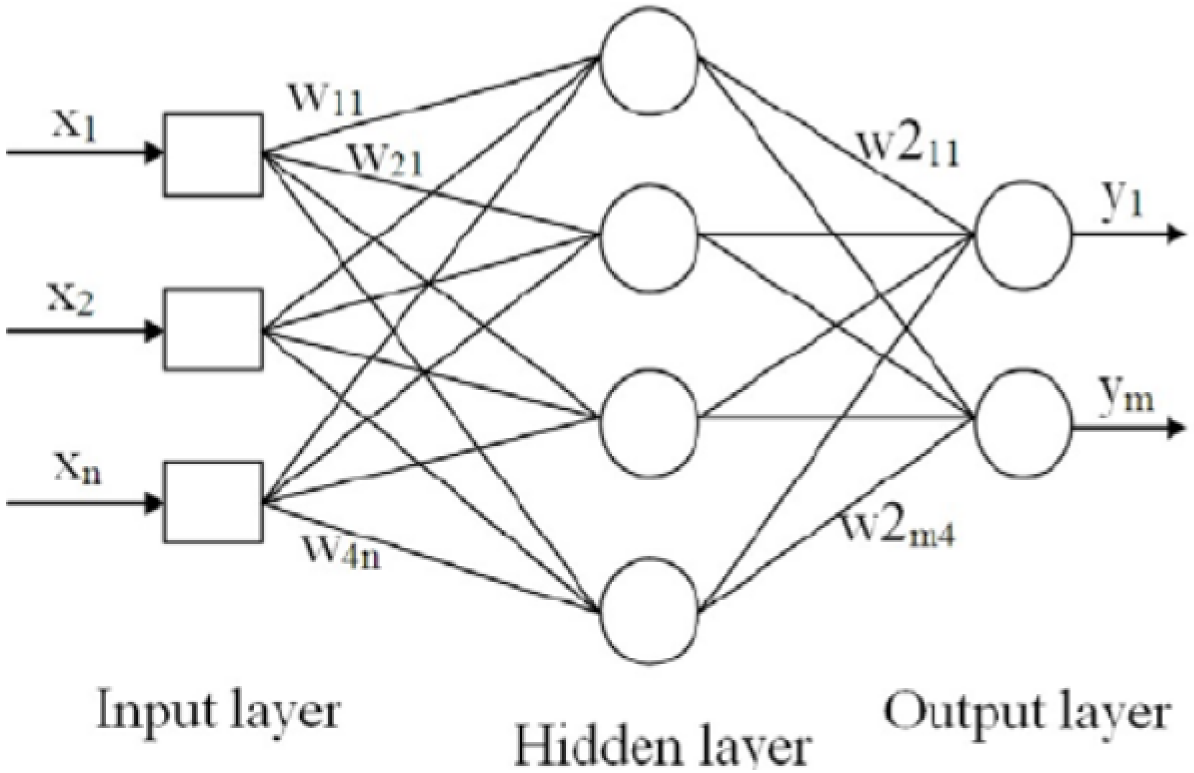
$$f(x) = \frac{1}{1+e^{-\beta x}}$$

$$f(x) = \tanh(\beta x)$$



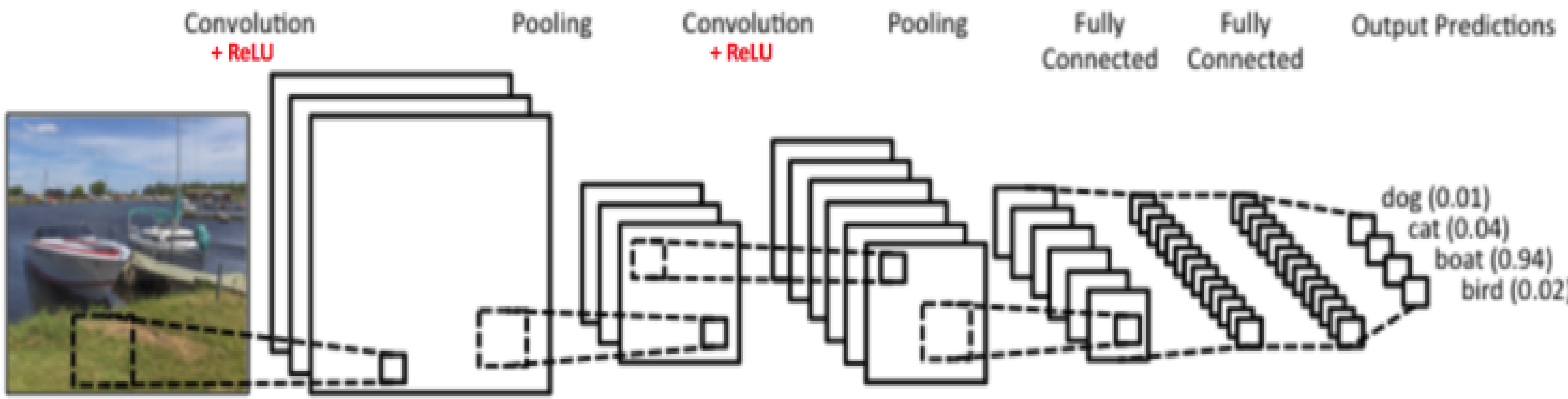
Very limited!

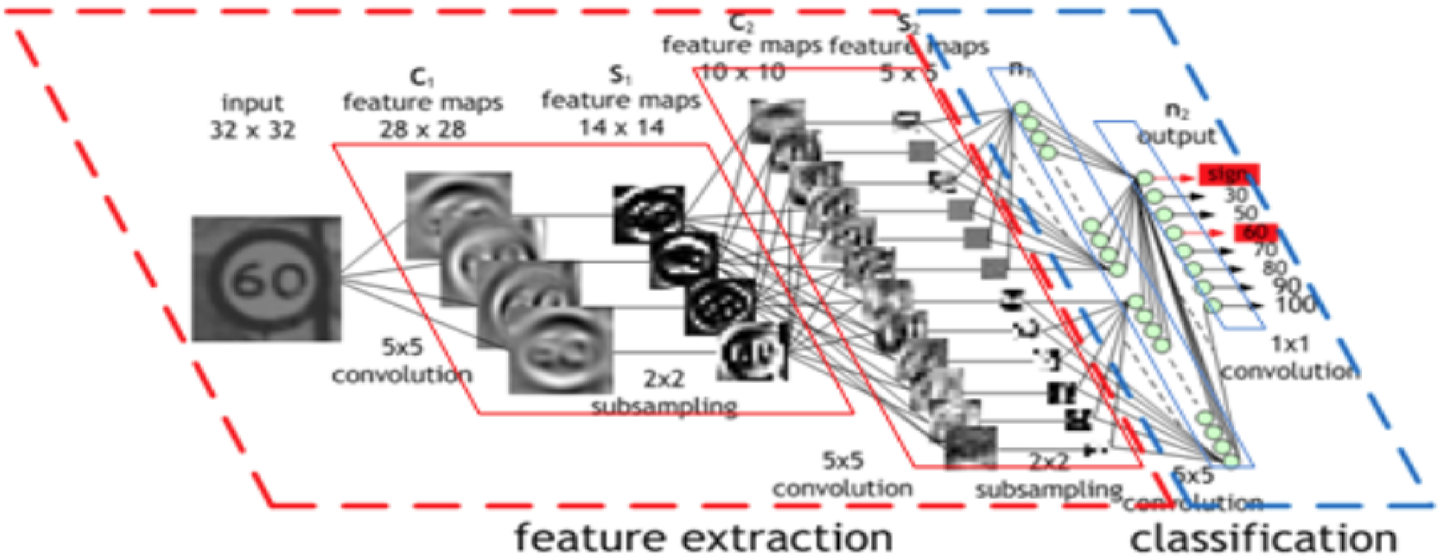
Multilayer perceptron



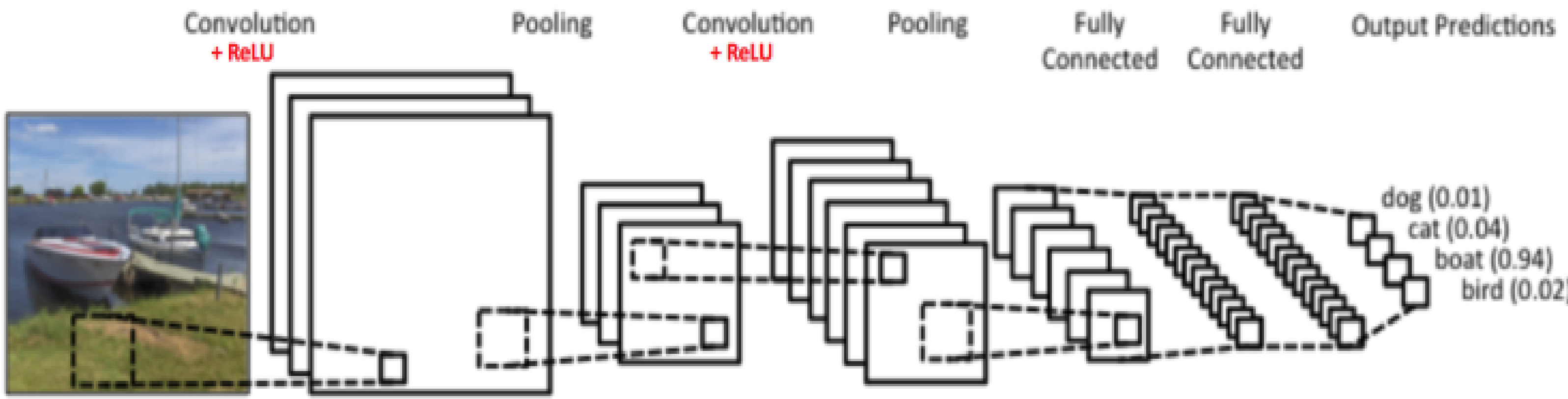
https://www.researchgate.net/profile/Junita_Mohamad-Saleh/publication/257071174/figure/fig3/AS:297526545666050@1447947264431/Figure-5-A-schematic-diagram-of-a-Multi-Layer-Perceptron-MLP-neural-network.png

Deep Neural Networks

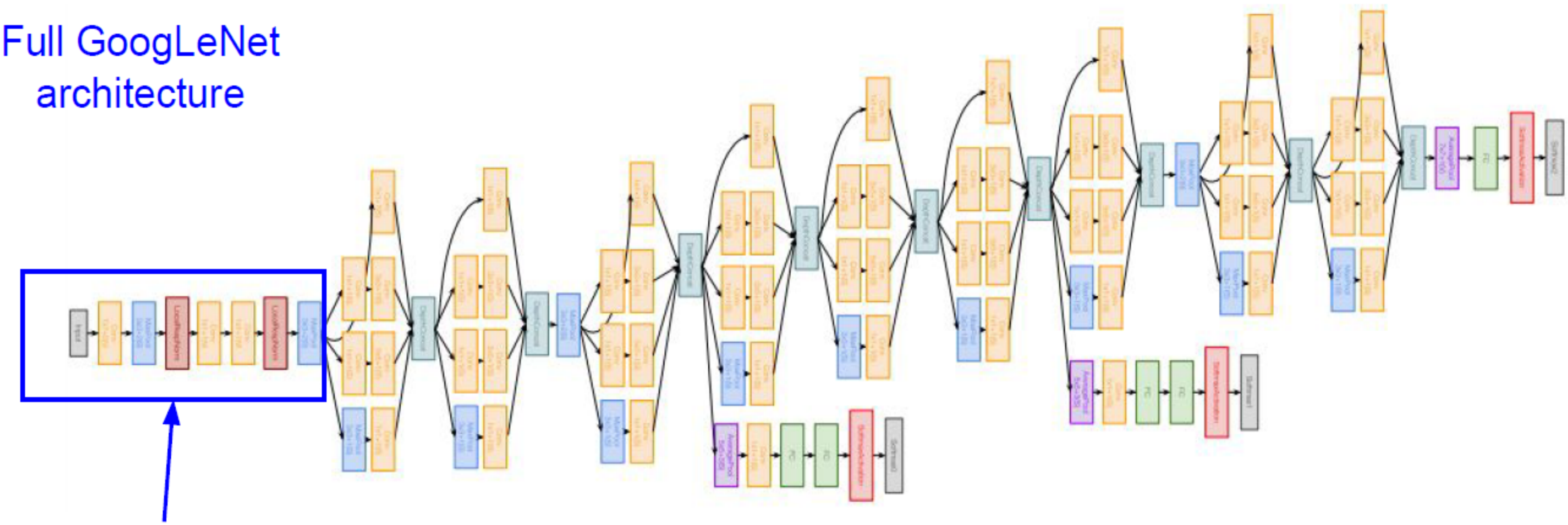




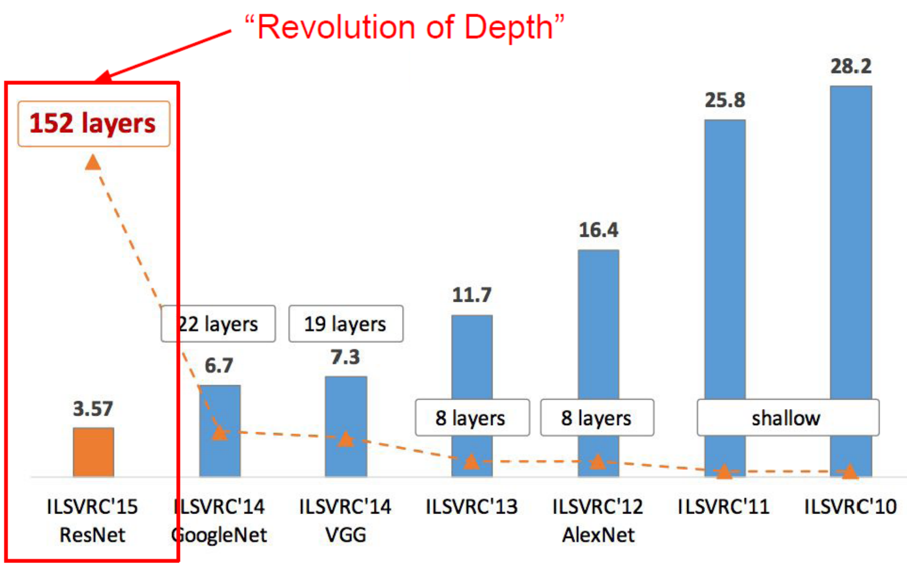
Deep Neural Networks

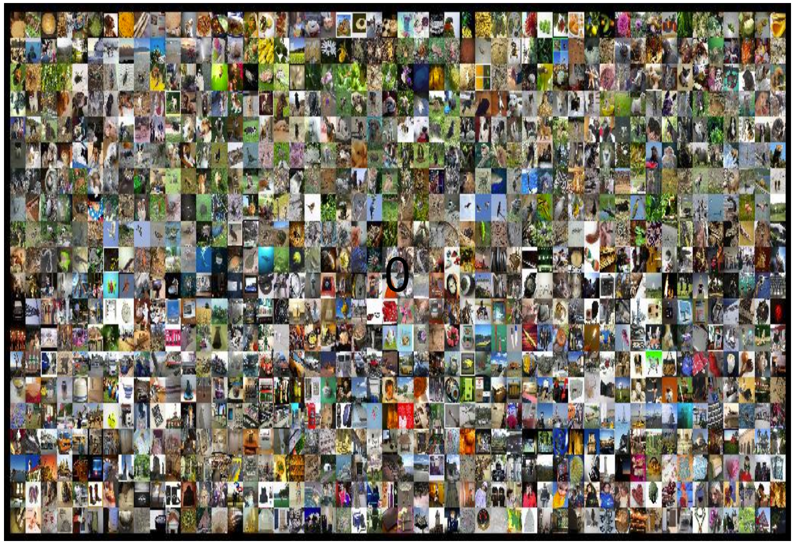


Full GoogLeNet architecture



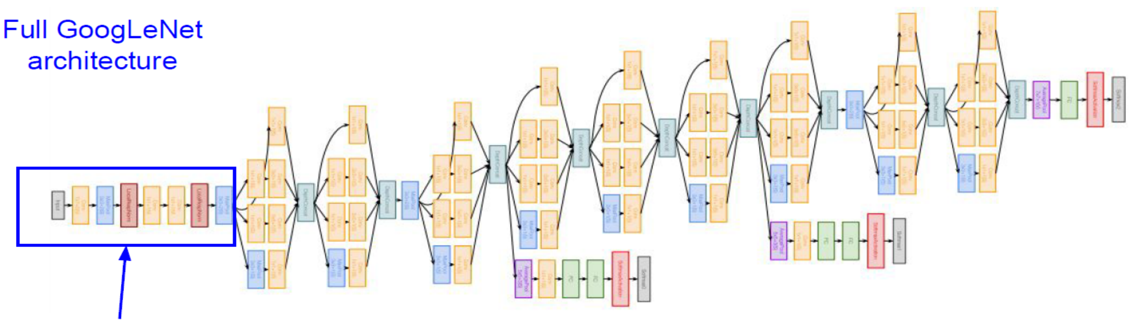
Deep Neural Networks



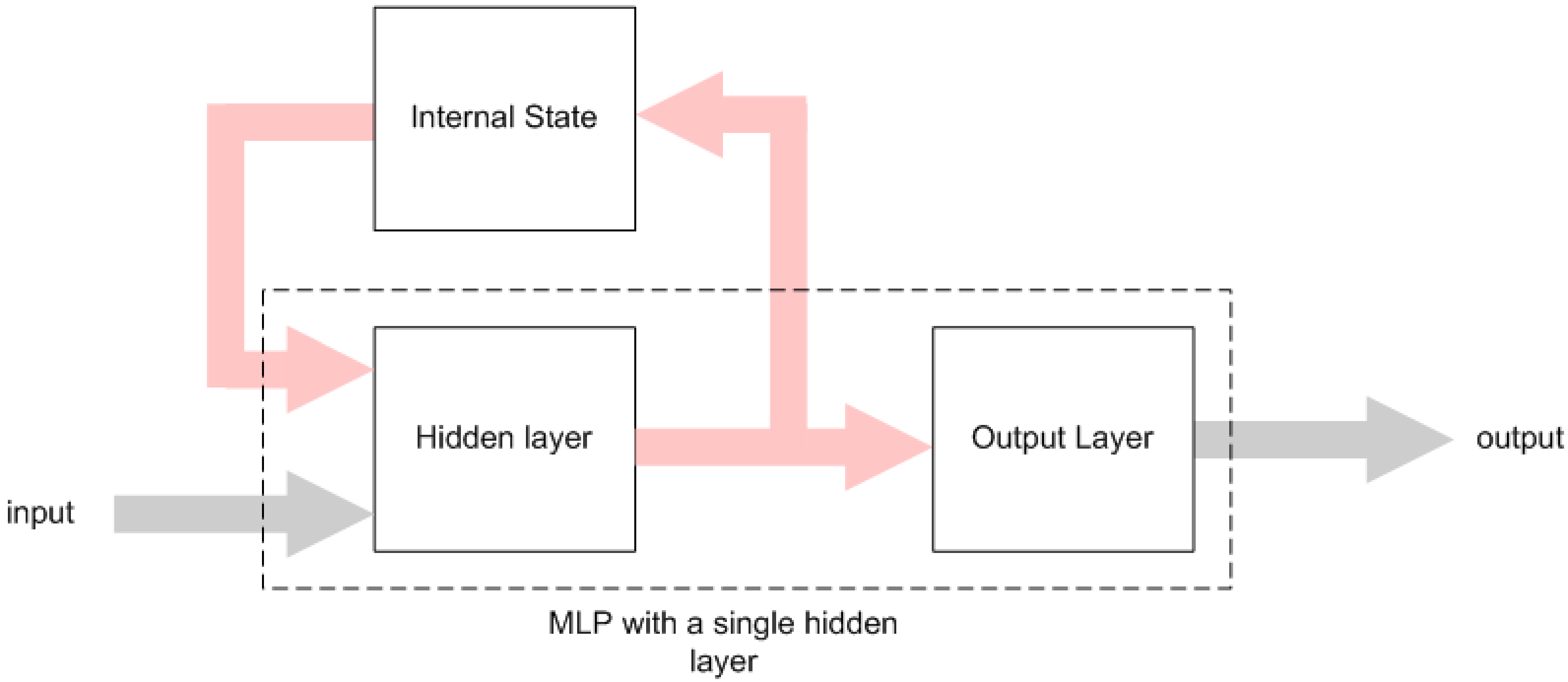


Very limited!

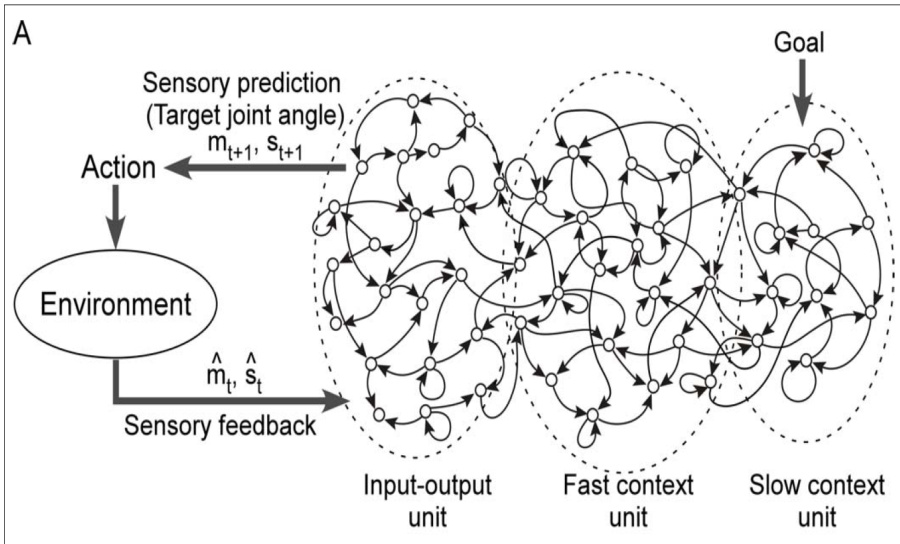
Full GoogLeNet architecture

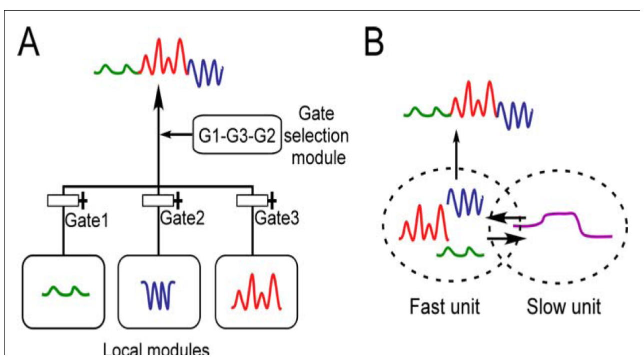


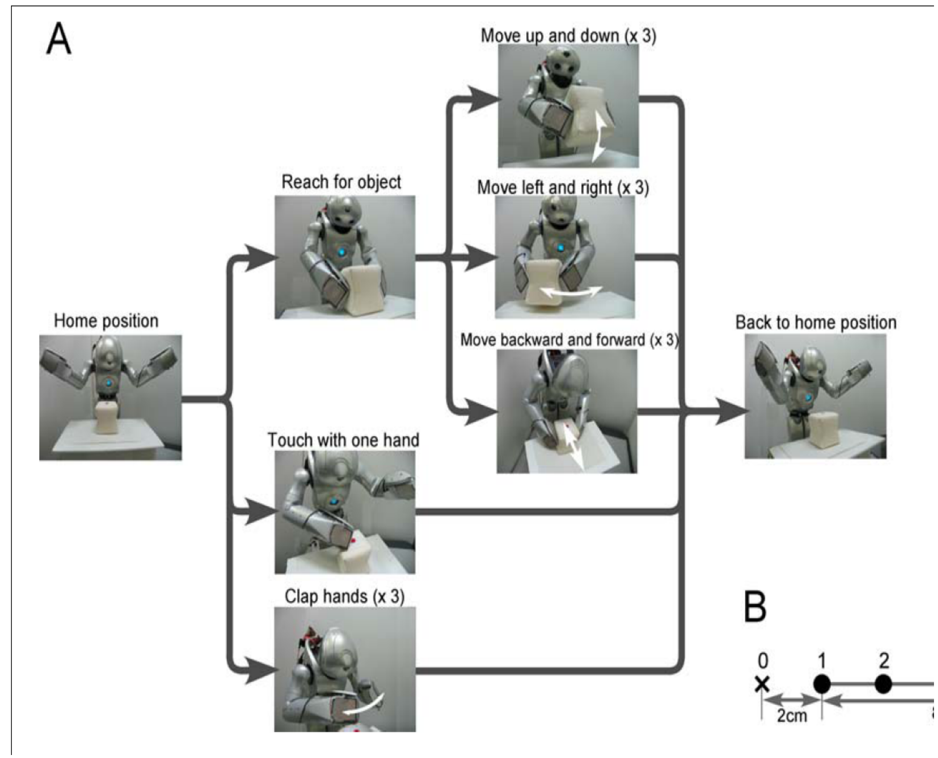
Recurrent neural networks



Recurrent neural networks







Yamashita, Yuichi, and Jun Tani. "Emergence of functional hierarchy in a multiple timescale neural network model: a humanoid robot experiment." PLoS Comput Biol 4.11 (2008): e1000220.

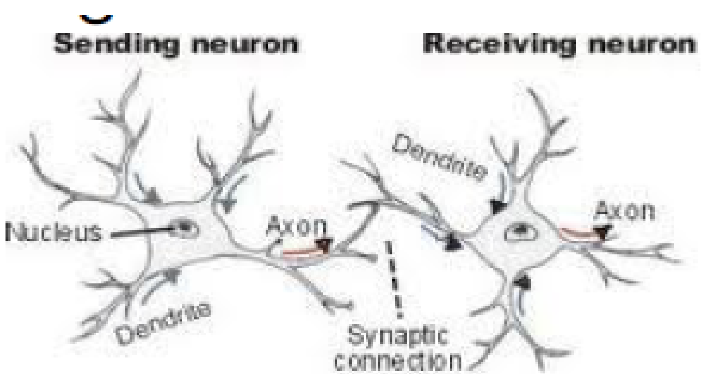
Hebb’s association principle

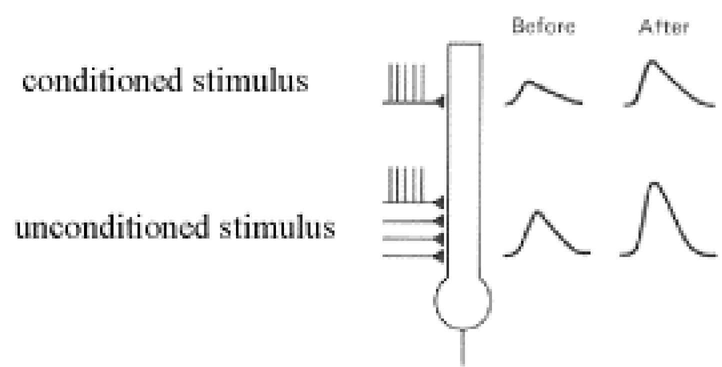
- Donald Hebb (1949)
  - Cell A – B simultenous excitation: growth / metabolic change
- Experiments (1966, 1973), confirming Hebb’s insight.
- The simple slogan to describe LTP is:

“Neurons that fire together, wire together.

Neurons that fire out of sync, fail to link.”

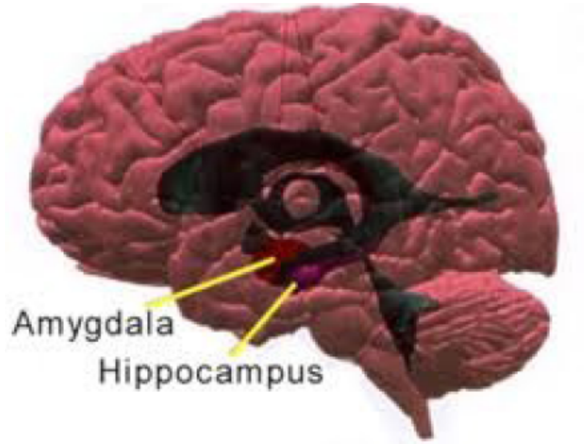
  - The neural network stores and retrieves associations, which are learned as synaptic connection.





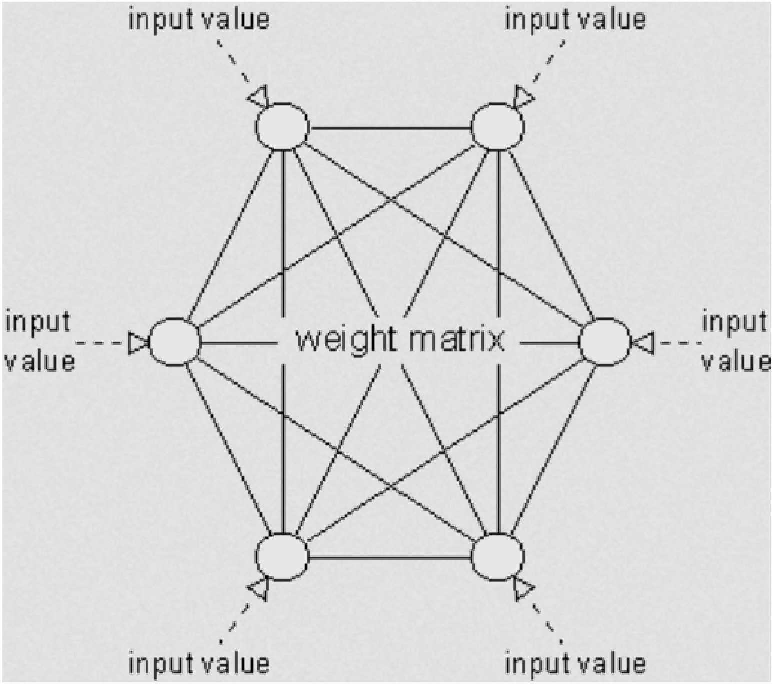
Hebb’s association principle and Human Learning

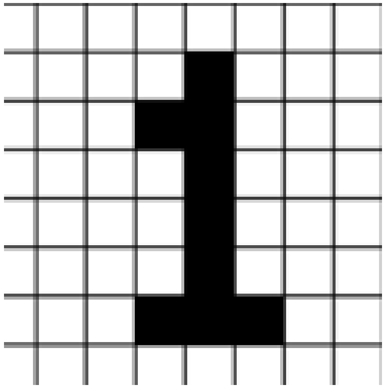
- Learning is to associate two events with each other.
- The main brain organ for learning/explicit memory is the hippocampus (of the limbic system) using Hebbian type.
- Human memory thus works in an associative or content-addressable way.



Hopfield Networks

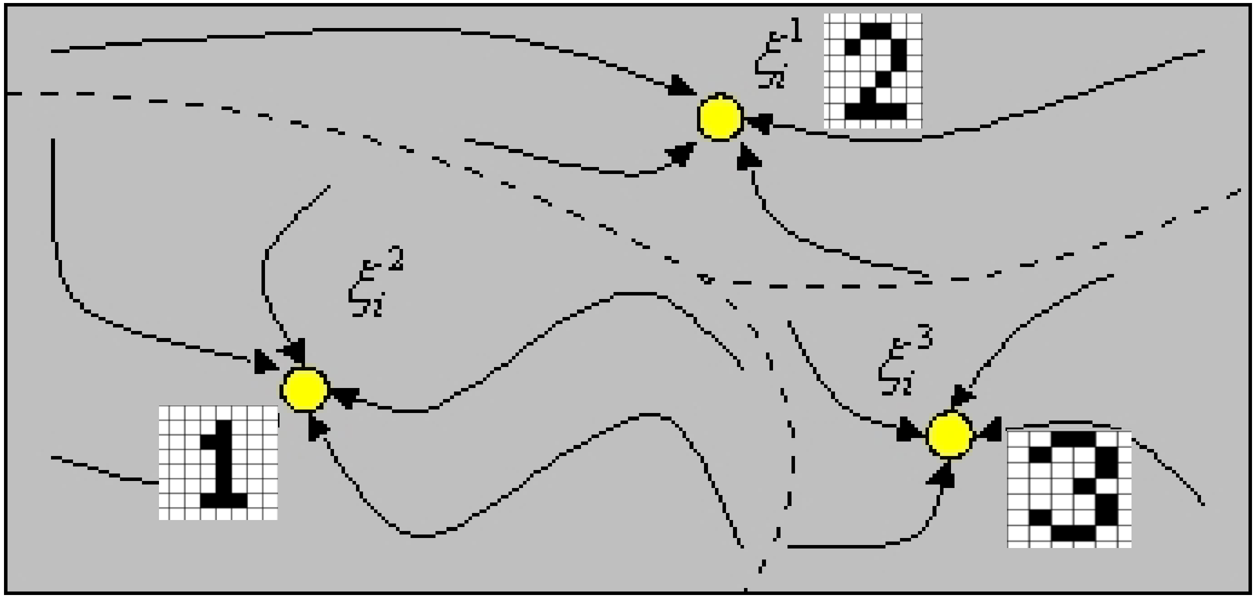
- A Hopfield Network is a model of associative memory. It is based on Hebbian learning but uses binary neurons.
- The associative memory problem is summarized as follows:
  - Store a set of p patterns P_i in such a way that when presented with a new pattern Q_i , the network responds by producing whichever one of the stored patterns most closely resembles Q_i .
- 0 or 1
- An associative memory can be thought as a set of attractors, each with its own basin of attraction.



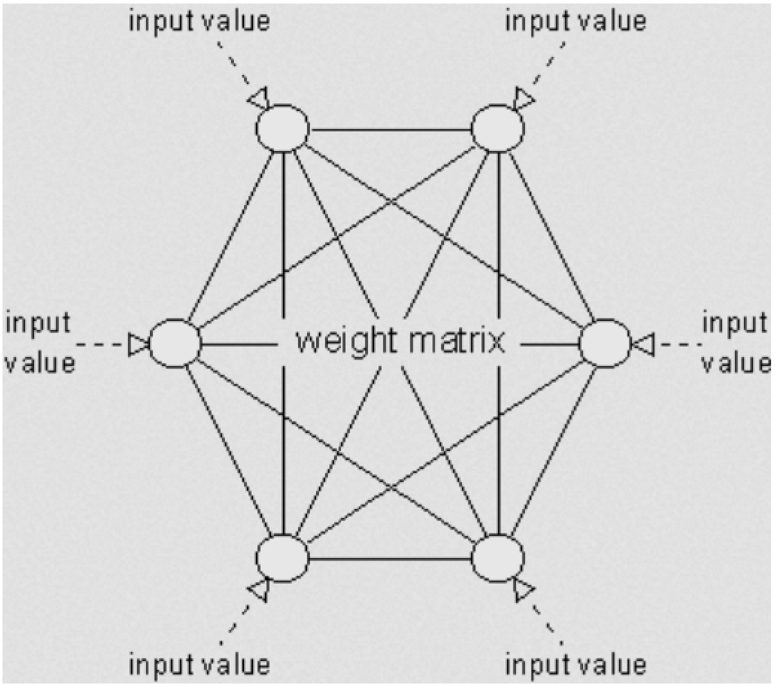


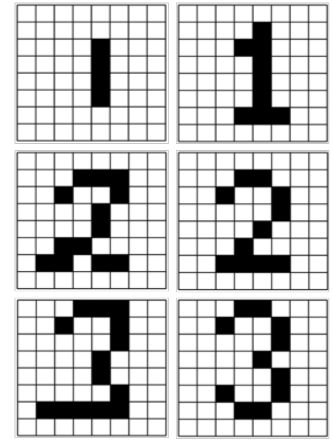
Hopfield Networks

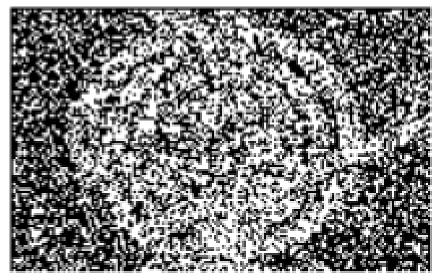
- The dynamics of the system carries a starting points into one of the attractors as shown in the next figure.

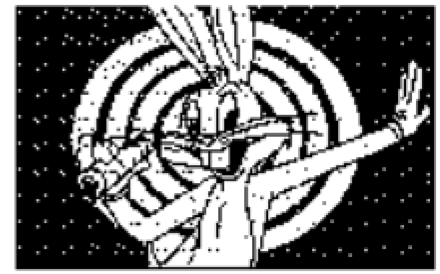


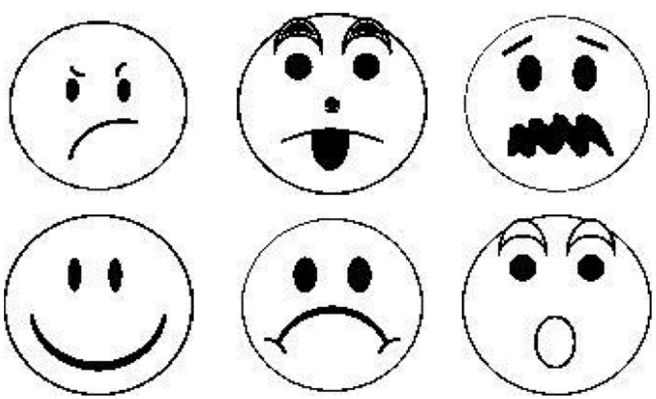
Hopfield Networks

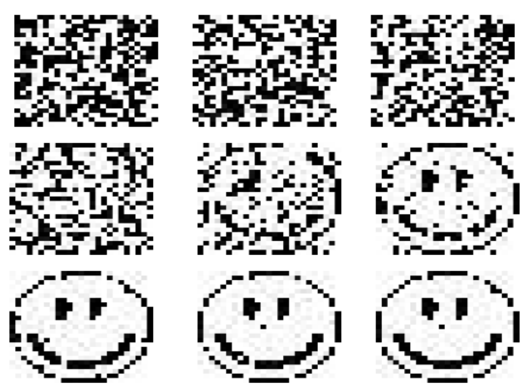








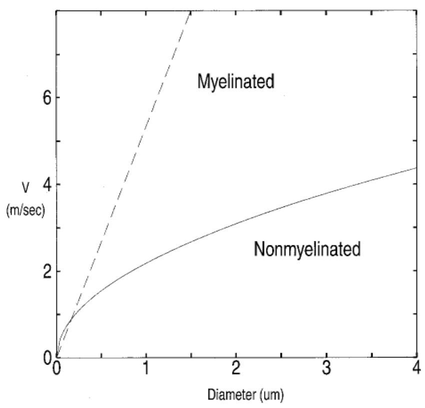


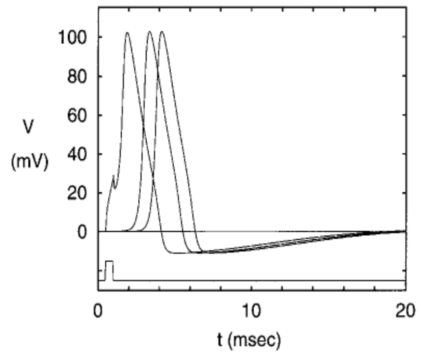


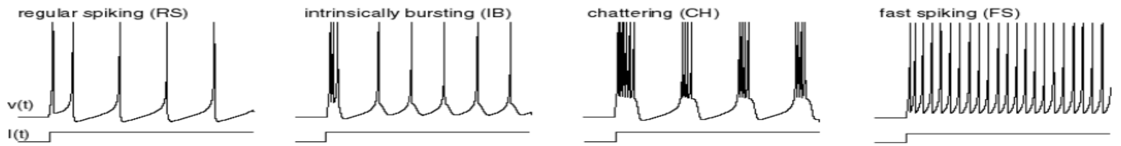
www.doc.ic.ac.uk/~ae/papers/Hopfield-networks-15.pdf

Spiking Neural Networks

- Increasing the level of realism
- Neuronal and synaptic state + concept of time.
- Neurons in the SNN do not fire at each propagation cycle, but rather fire only when a membrane potential reaches a specific value.
- When a neuron fires, it generates a signal which travels to other neurons which, in turn, increase/decrease their potentials.
- The current activation level (modeled as some differential equation) is normally considered to be the **neuron's state**, with incoming spikes **pushing this value higher**, and then either firing or decaying over time



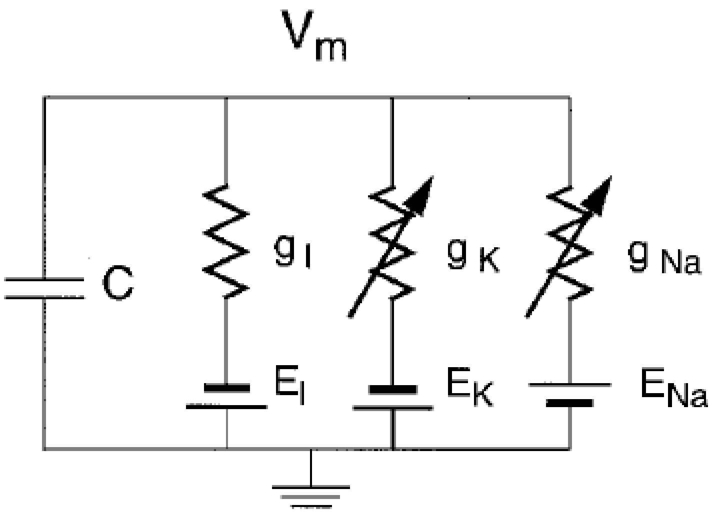




Hodgkin-Huxley Model

- Mathematical model that describes how action potentials in neurons are initiated and propagated
- Alan Lloyd Hodgkin and Andrew Fielding Huxley described the model in 1952 to explain the ionic mechanisms underlying the initiation and propagation of action potentials in the squid giant axon
- Terminology:
  - Channel: Flow of ions through membrane proteins
  - Concentration gradient: High sodium concentration outside the membrane
  - Reversal potential: Reduction of the gradient to zero
  - Electrical gradient: By sodium flow
  - Rest potential: -65mV
  - Threshold: At around -50mV, sodium channels open up

Hodgkin-Huxley Model



$$C\frac{dV_m}{dt} = g_l(E_l - V_m) + g_{\mathrm{Na}}(E_{\mathrm{Na}} - V_m) + g_{\mathrm{K}}(E_{\mathrm{K}} - V_m)$$

$$g_{\mathrm{Na}} = \bar{G}_{\mathrm{Na}} \cdot m(t)^3 h(t)$$
$$g_{\mathrm{K}} = \bar{G}_{\mathrm{K}} \cdot n(t)^4$$

$$\frac{dm}{dt} = \frac{m_\infty(V_m) - m}{\tau_m(V_m)}$$
$$\frac{dh}{dt} = \frac{h_\infty(V_m) - h}{\tau_h(V_m)}$$
$$\frac{dn}{dt} = \frac{n_\infty(V_m) - n}{\tau_n(V_m)}$$

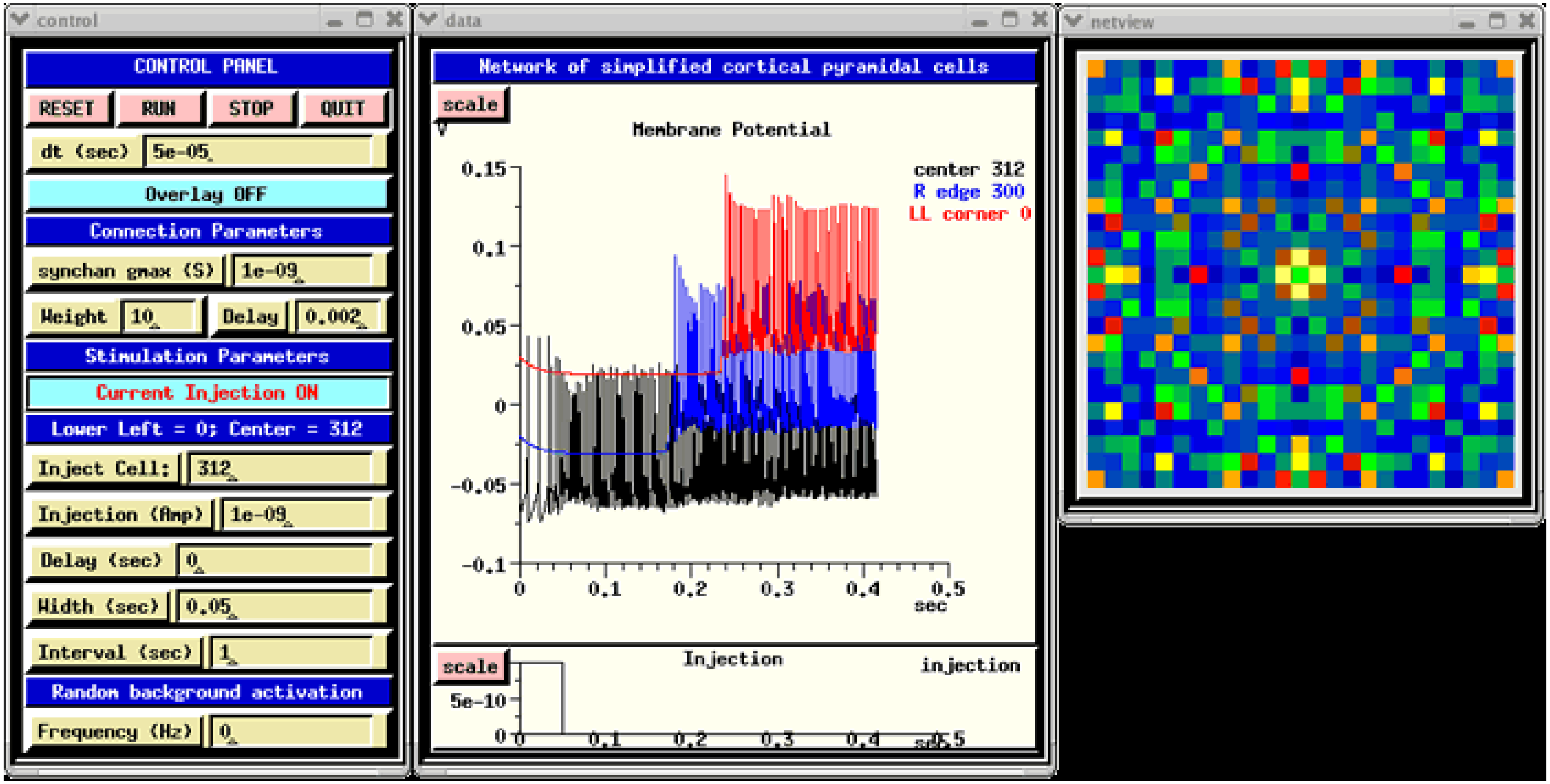
$$x_\infty = \frac{\alpha_x}{\alpha_x + \beta_x}$$
$$\tau_x = \frac{1}{\alpha_x + \beta_x}$$

$$\alpha_m = \frac{0.1(V_m - 40)}{e^{(V_m - 40)/10} - 1} \qquad \beta_m = 4e^{(V_m - 65)/18}$$
$$\alpha_h = 0.07e^{(V_m - 65)/20} \qquad \beta_h = \frac{1}{e^{(V_m - 35)/10} + 1}$$
$$\alpha_n = \frac{0.01(V_m - 55)}{e^{(V_m - 55)/10} - 1} \qquad \beta_n = 0.125e^{(V_m - 65)/80}$$

GENESIS Simulation System

- GEneral NEural SImulation System
- Models channels, cells and networks
- http://www.genesis-sim.org
- Creating a realistic model of a neuron:
  - Set the passive membrane parameters (membrane resistance and capacitance, axial resistance, and membrane resting potential for each of the compartments.
  - Populate the compartments with ionic conductances ("channels"), or other related neural elements.
  - Link compartments for the soma and dendrites together with appropriate messages to make a cell.

GENESIS Simulation System



NEURON Simulation Environment

- In *NEURON*, the neuron's geometry is described in terms of cylindrical **sections**
- Channel properties are set within sections
- You can add “cables”, and produce hierarchical structures
- Over a thousand papers published
- Hines, M. L. and Carnevale, N. T., 2001.
- http://www.neuron.yale.edu

CmpE 489/COGS 500: Cognitive Science

Week 4

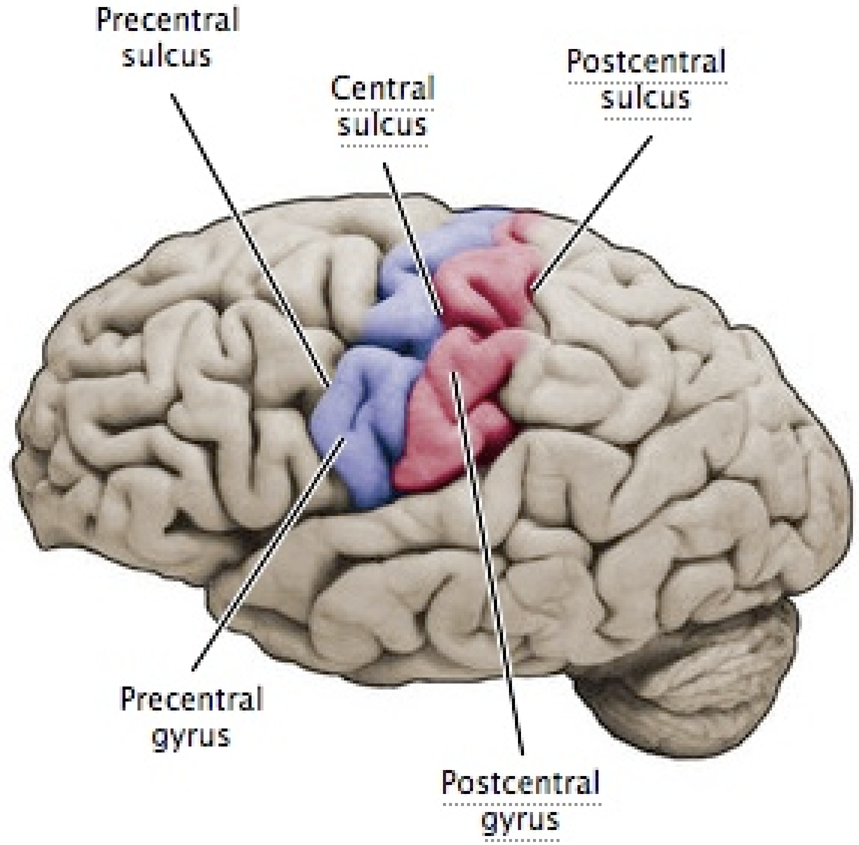
Computational Models of Neurons
Representation of Sensory Information
Multisensory integration in cortex

Adapted from Albert Ali Salah's slides

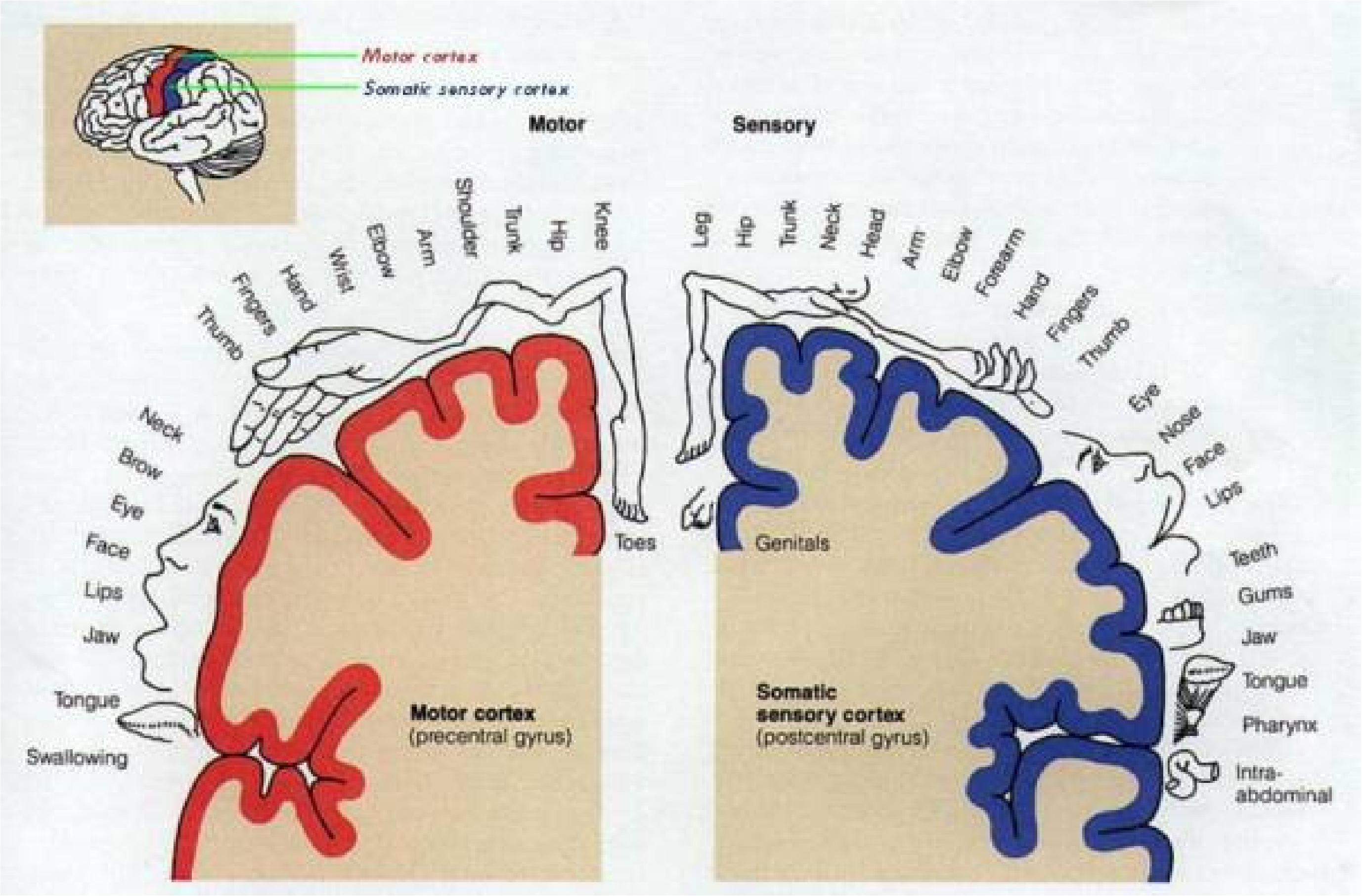
Overview

- Processing of sensory information in the brain:
  - Motor and sensory areas
  - Visual pathways
- Overview of senses

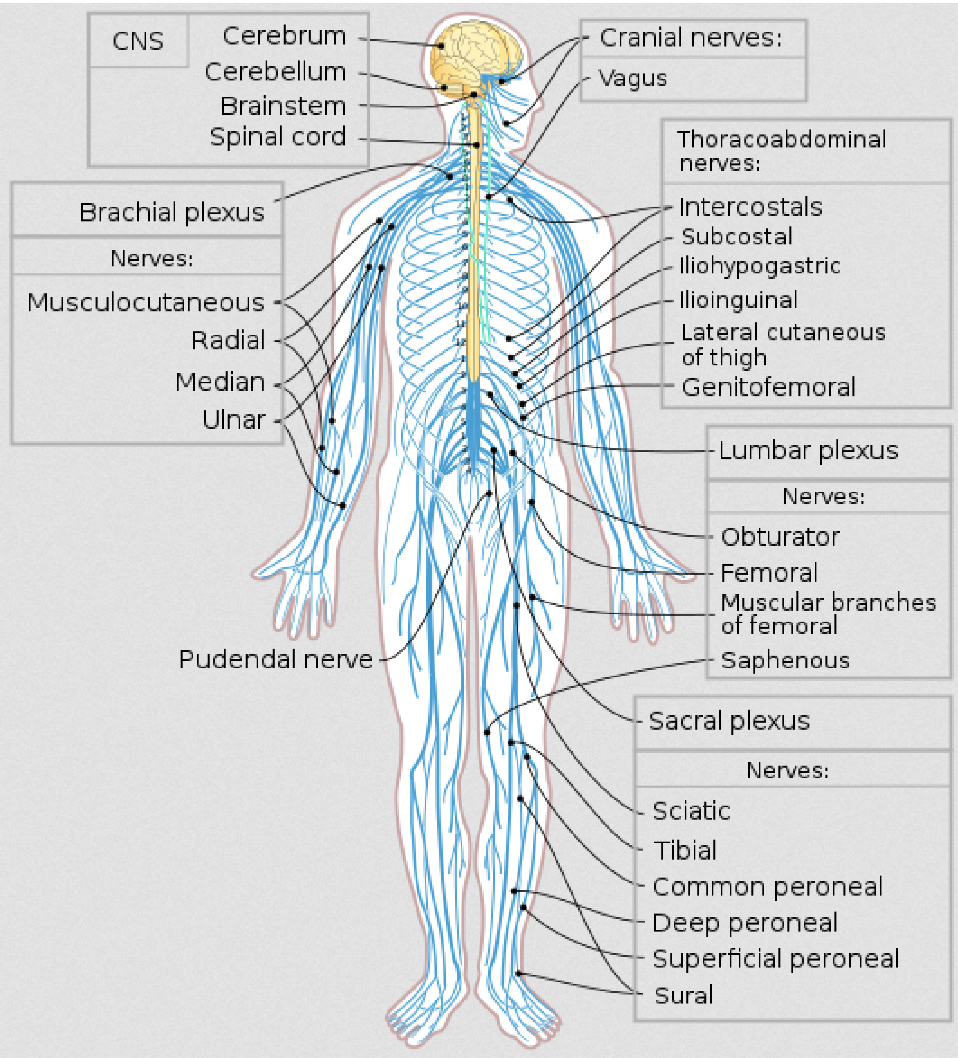
Primary motor and sensory areas

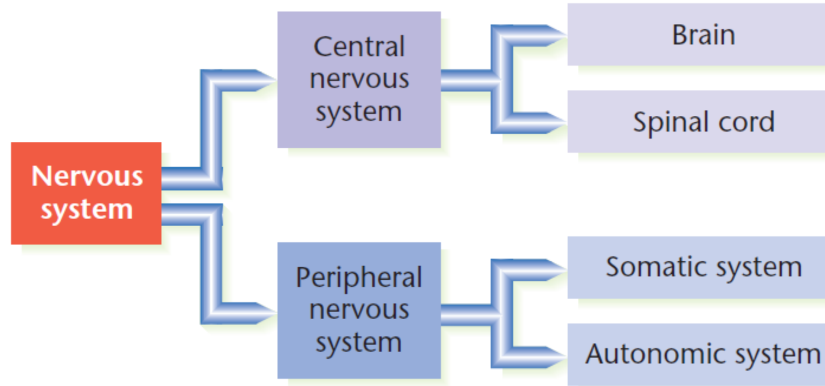


Organization of sensory and motor cortices



Nervous system



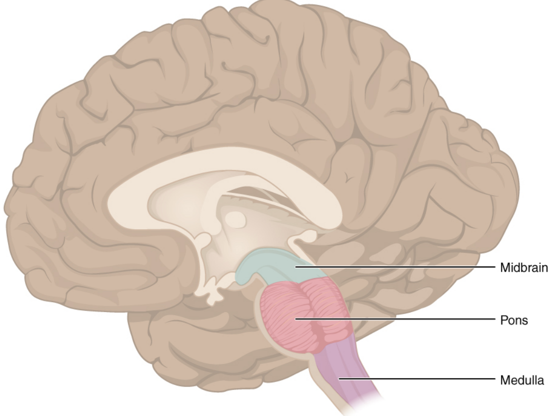


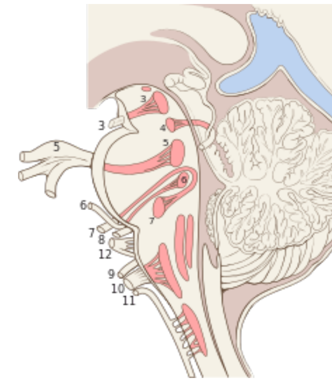
Somatic system: to/from the sense receptors, muscles, and surface of body – voluntary motor functions

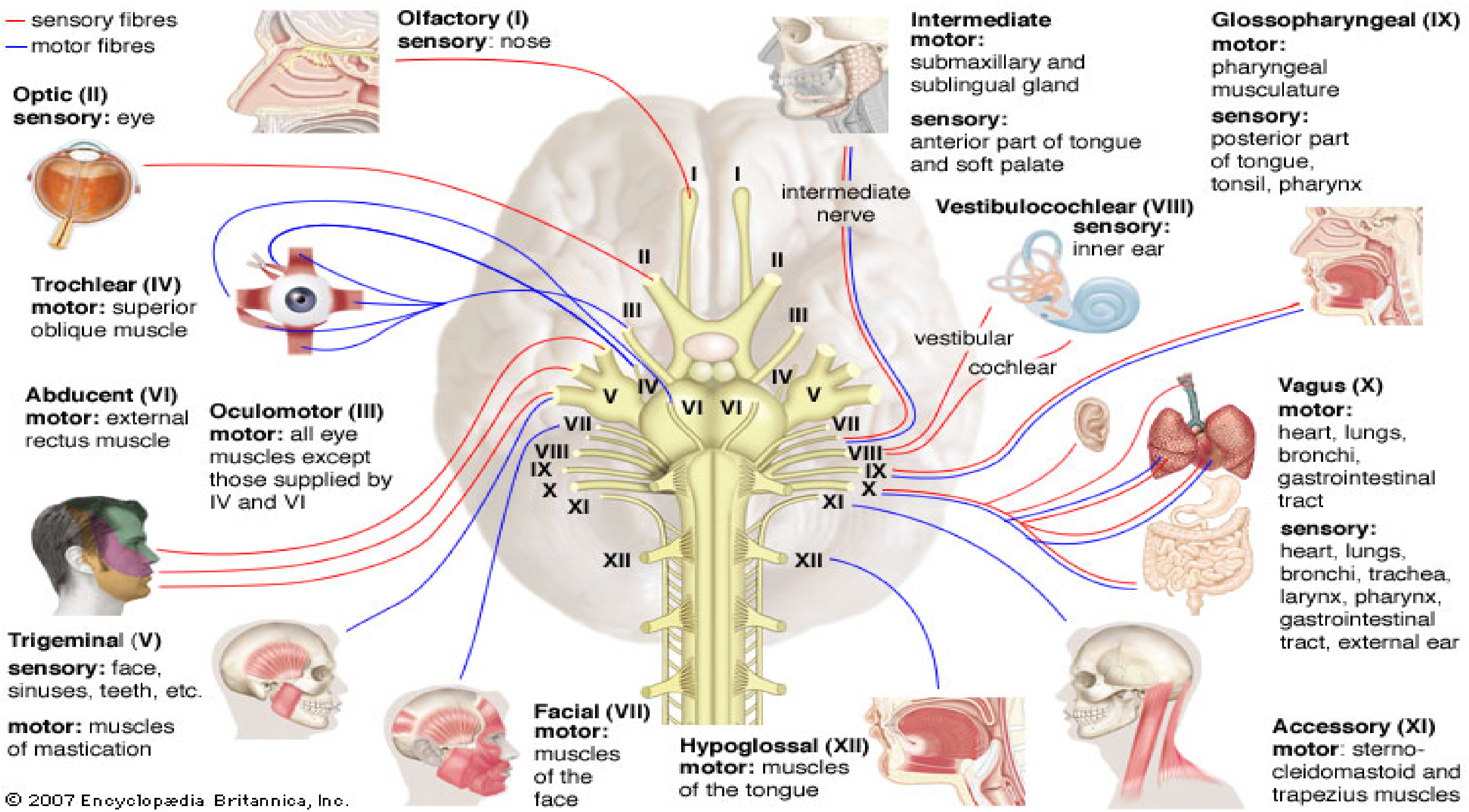
- Sensory nerves: transmit information about external stimulation from skin/muscles/joints, e.g. pain, pressure, temperature
- Motor nerves: from CNS to muscles

Autonomic: involuntary control system. internal organs and glands for automatic and involuntary actions such as beating of the heart. Respiration, heart rate, digestion

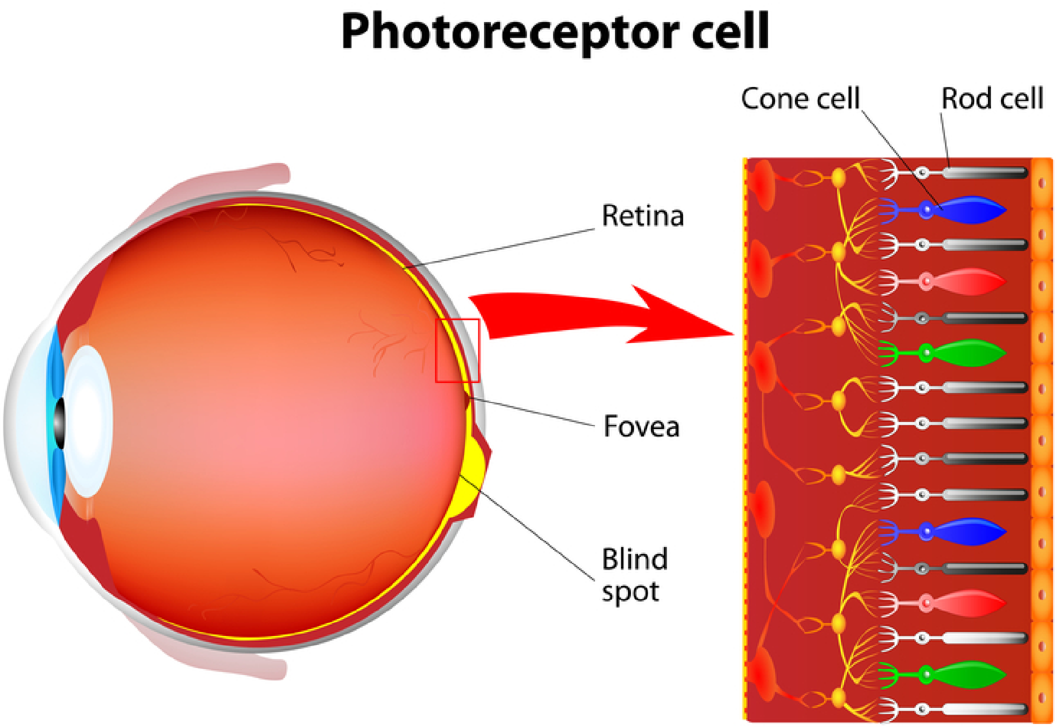
Cranial nerves



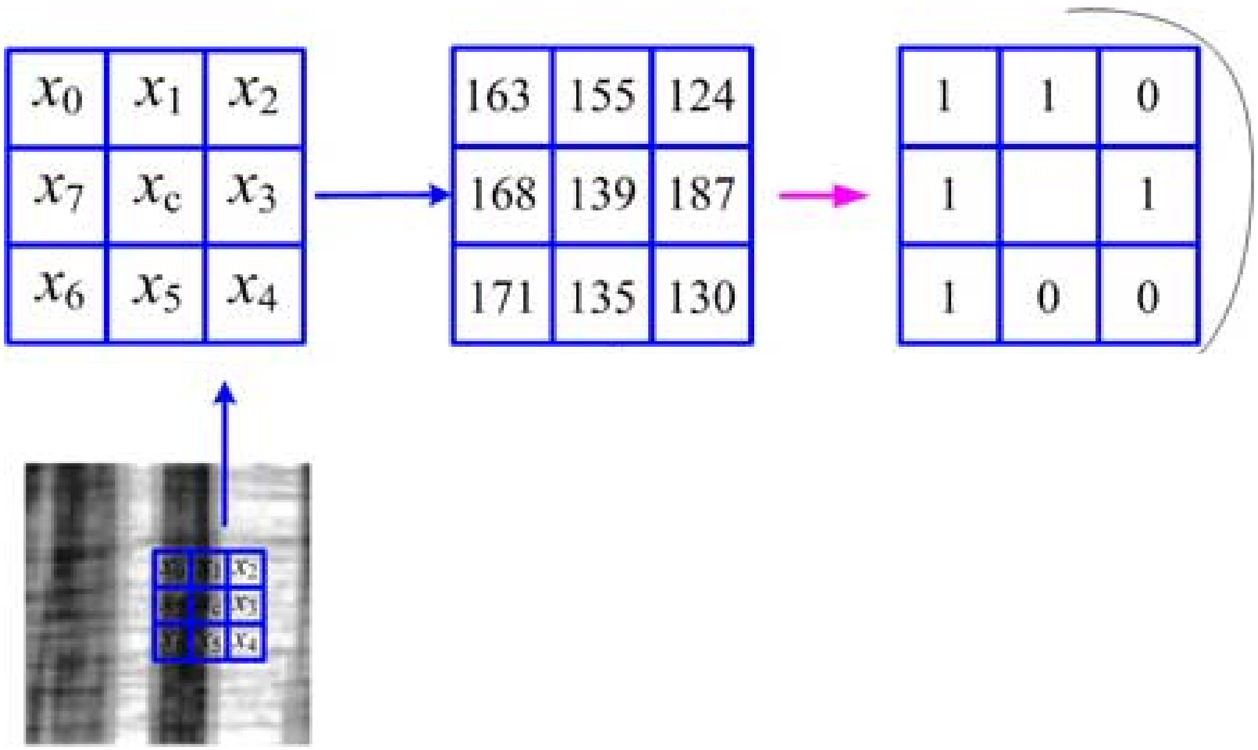




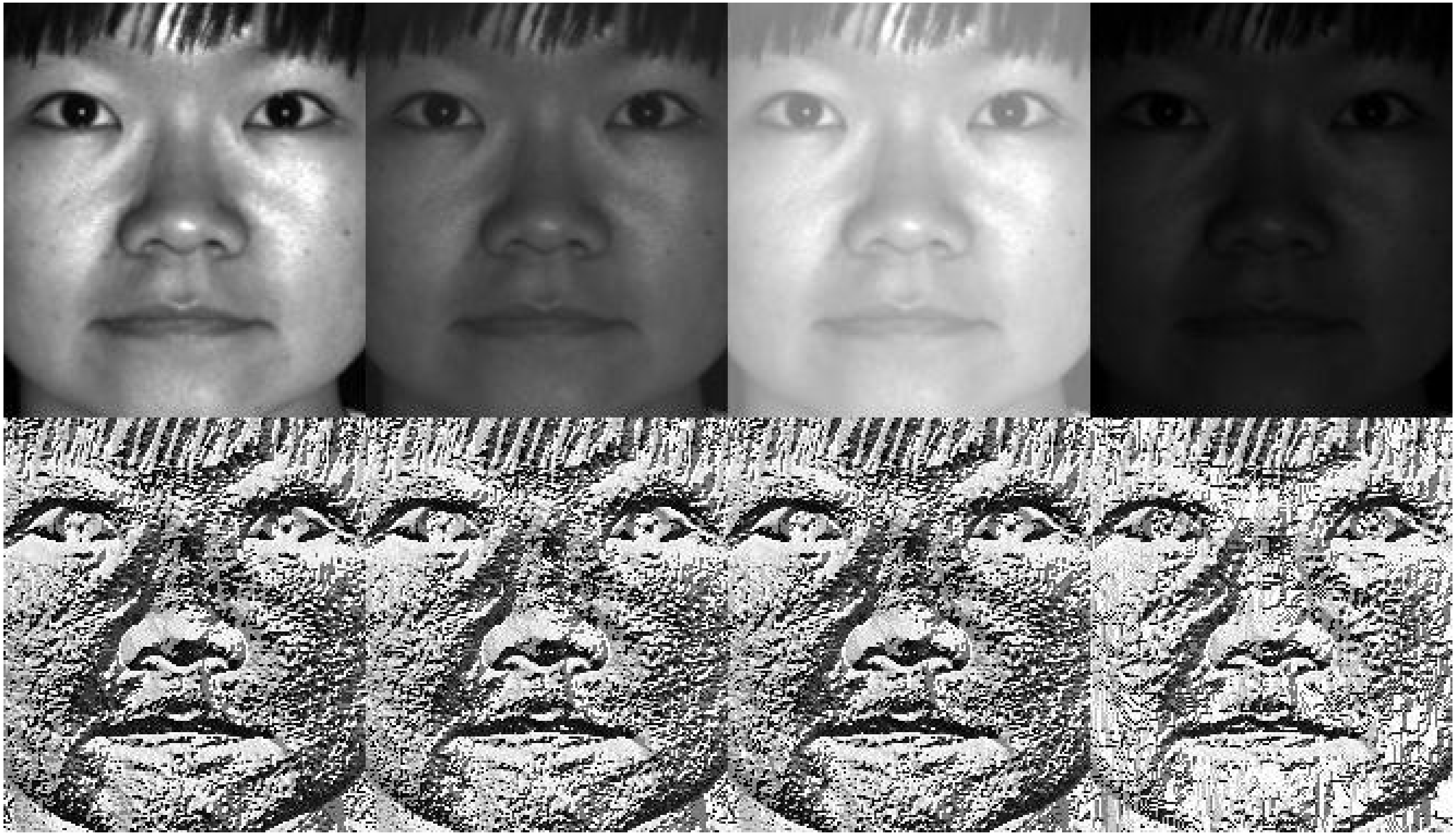
Eye and retina



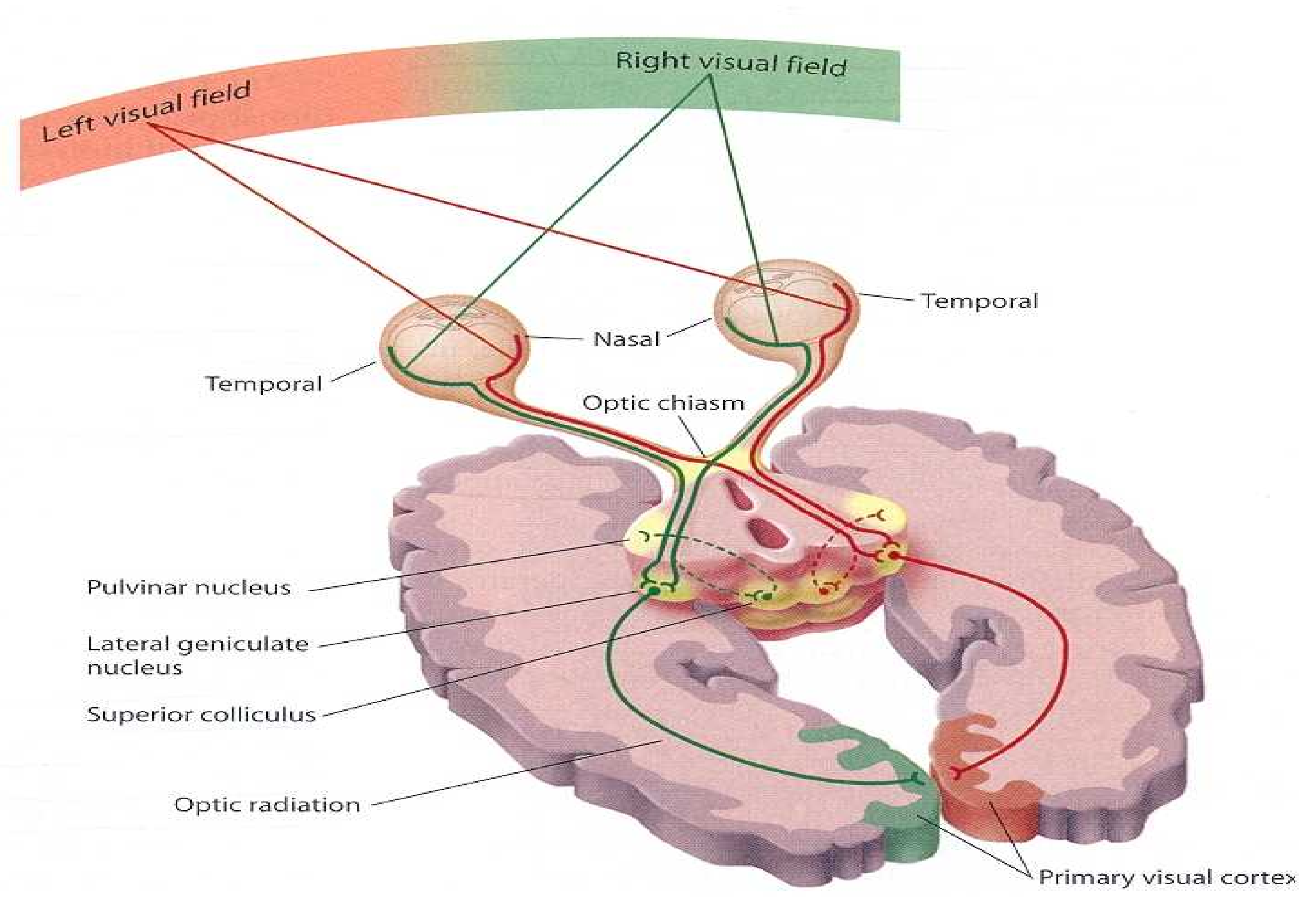
Local binary patterns



Illumination invariance



Visual pathways

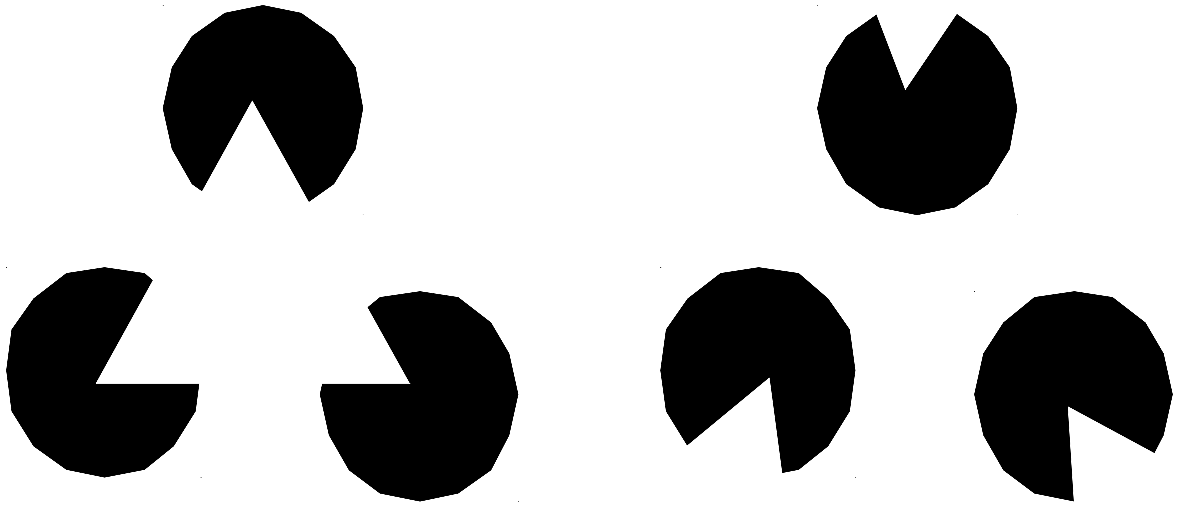


Senses

- How many senses do we have?
  - Five traditional senses: sight, touch, audition, taste, and smell
  - Proprioceptive senses:
    - . heat and cold, gravitation, acceleration, pain..
  - Sub-senses: motion, colour, form, brightness, texture, and contrast of objects.

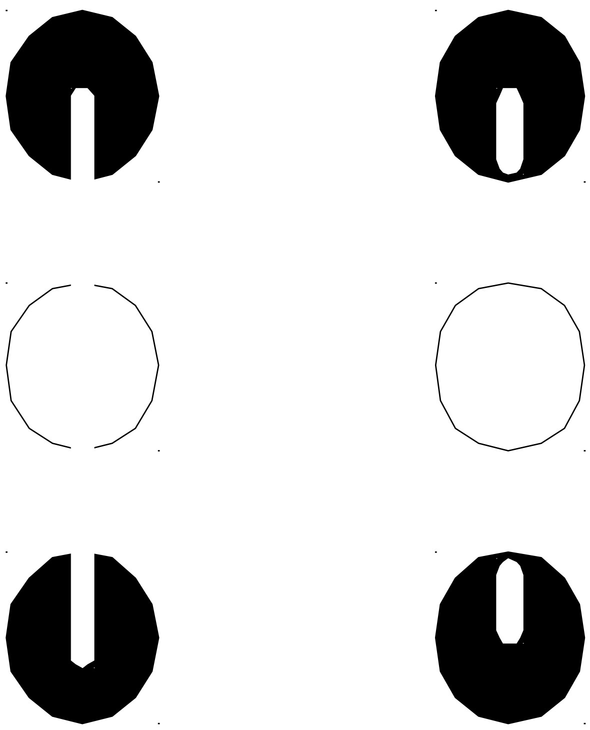
"Sensation is the body's detection of external or internal stimulation. Perception utilizes the brain to make sense of the stimulation."
wikipedia

See the triangle?



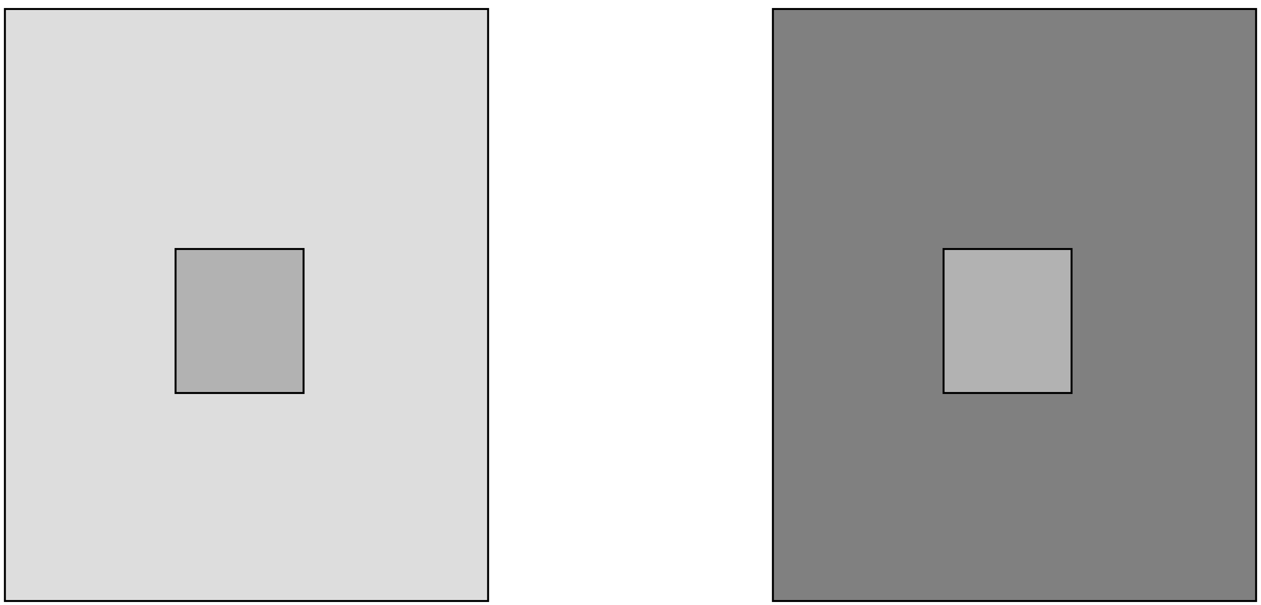
Adapted from Michael E. Goldberg, M.D.

See the white bar?



Adapted from Michael E. Goldberg, M.D.

Which small square is darker?



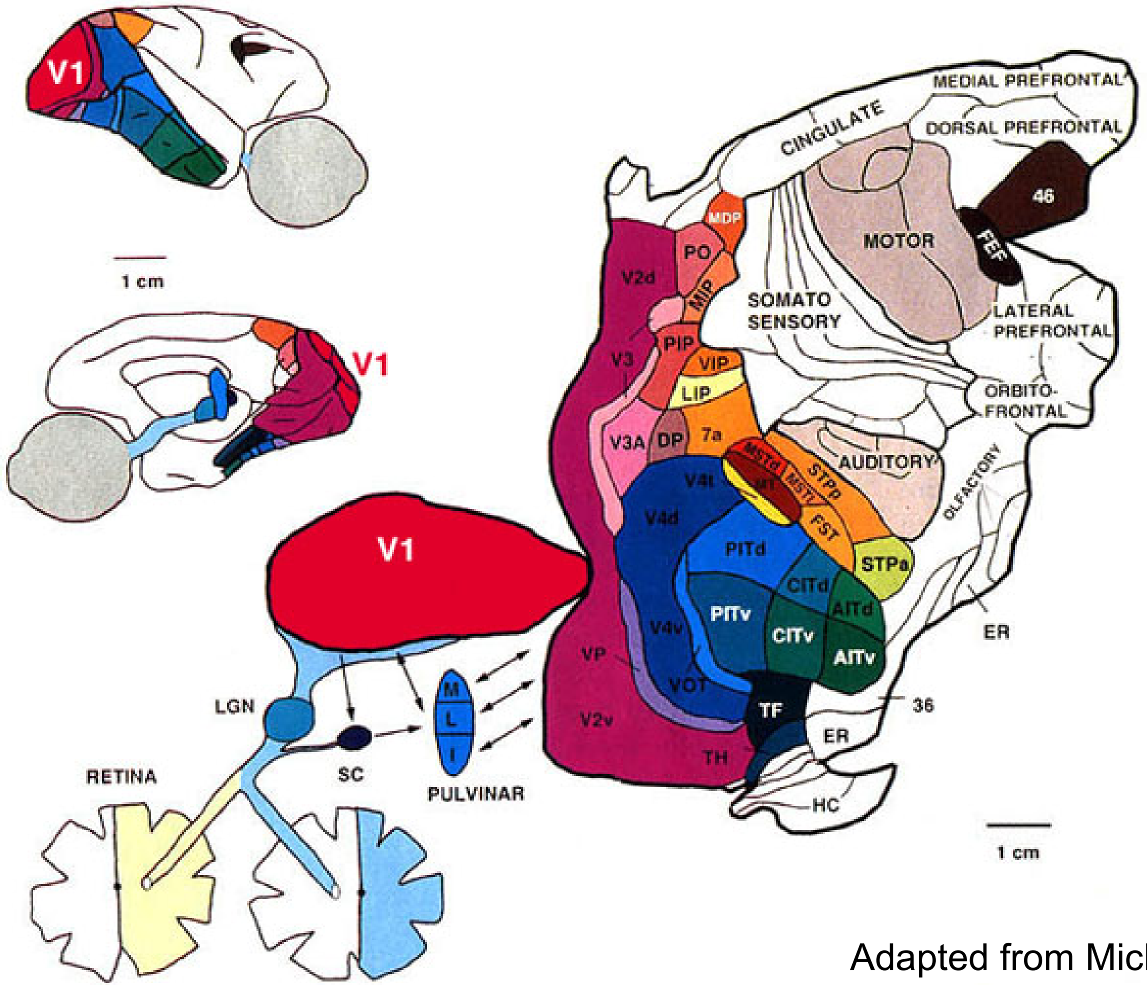
Adapted from Michael E. Goldberg, M.D.

So

- Your visual system does not measure and report the exact physical nature of the visual world.
- It collects some data, and makes guesses.
- Optical illusions take advantage of the guessing strategies.

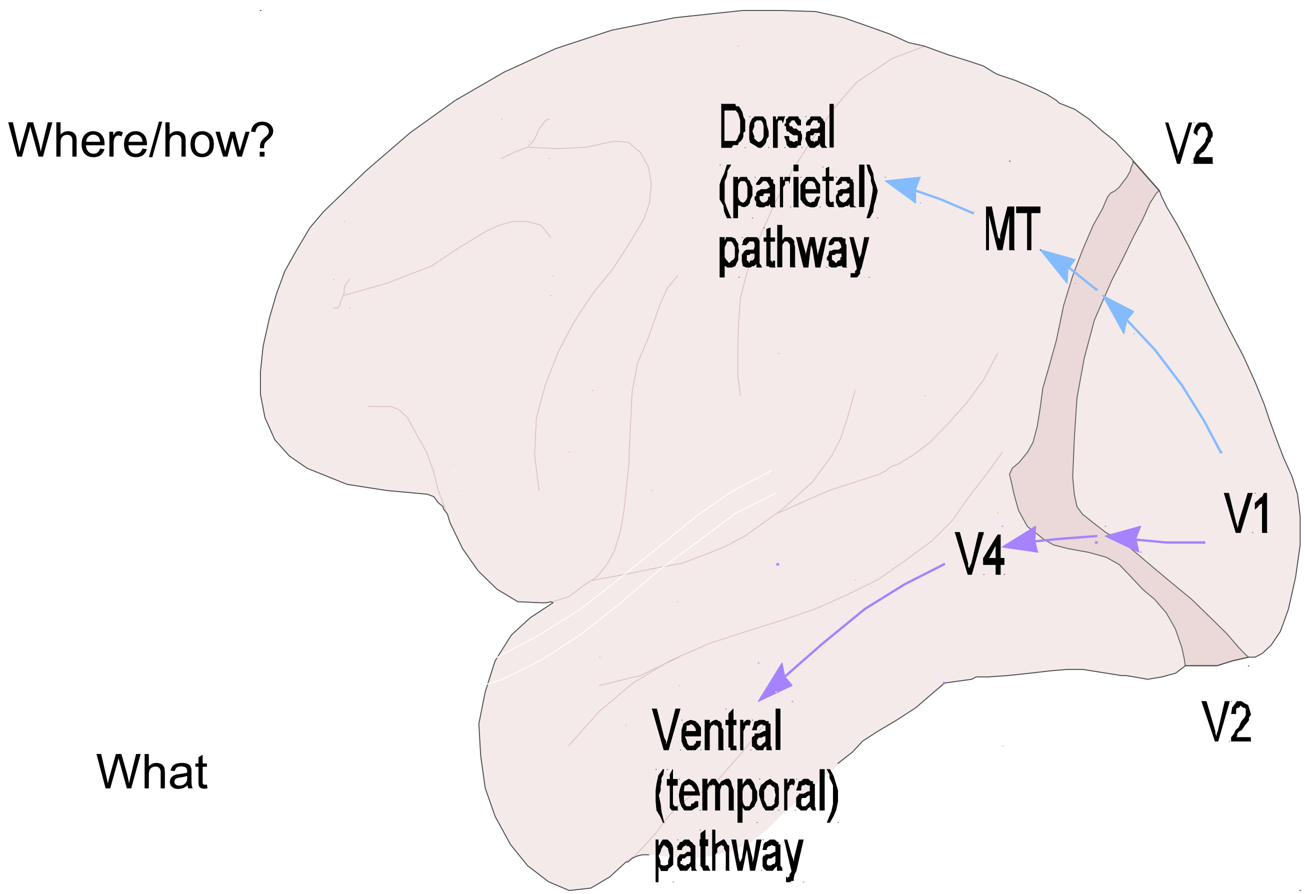
Adapted from Michael E. Goldberg, M.D.

Roughly 40% of cerebral cortex is involved in vision



Adapted from Michael E. Goldberg, M.D.

Two cortical visual streams subserve two different visual functions.



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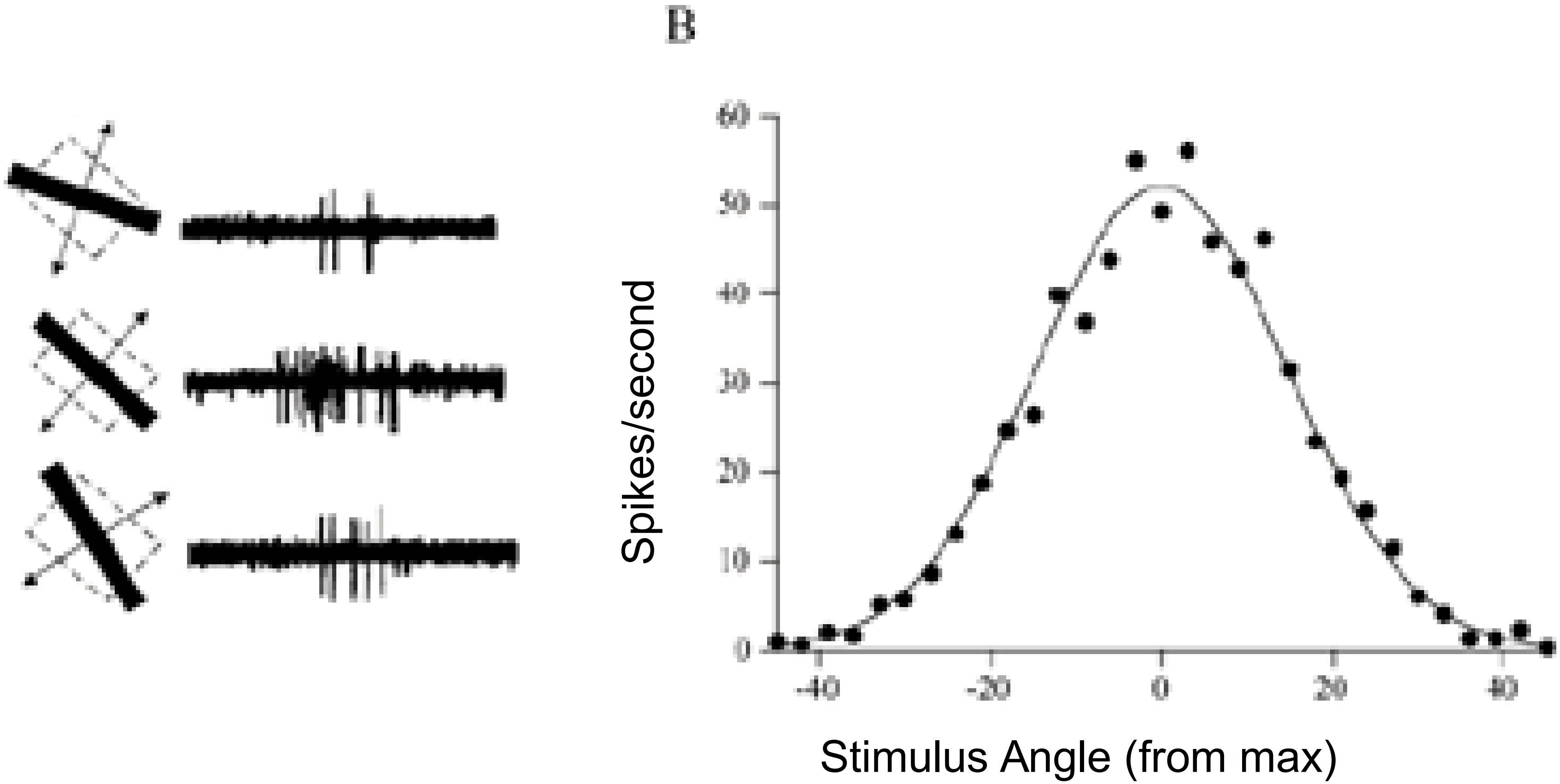
Orientation tuning in a V1 simple cell



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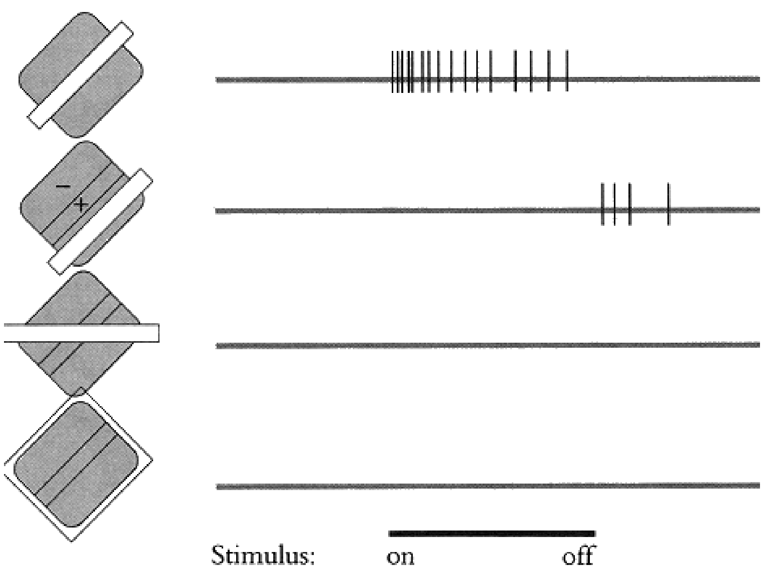
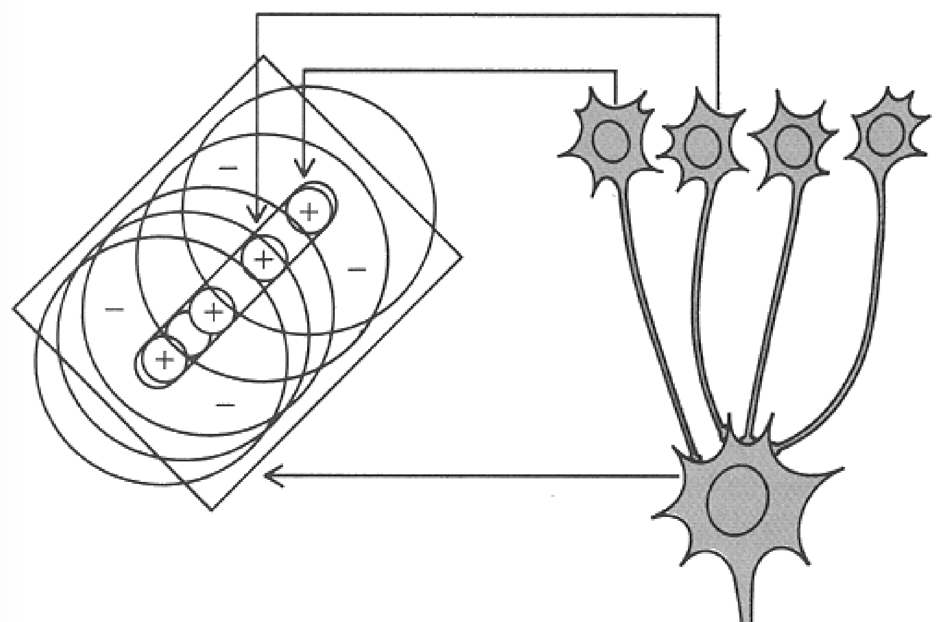
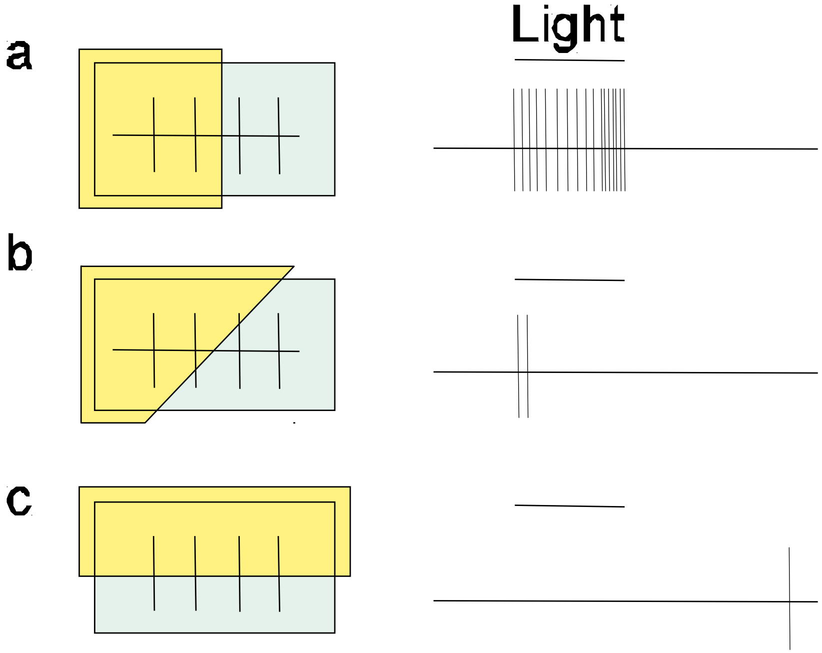


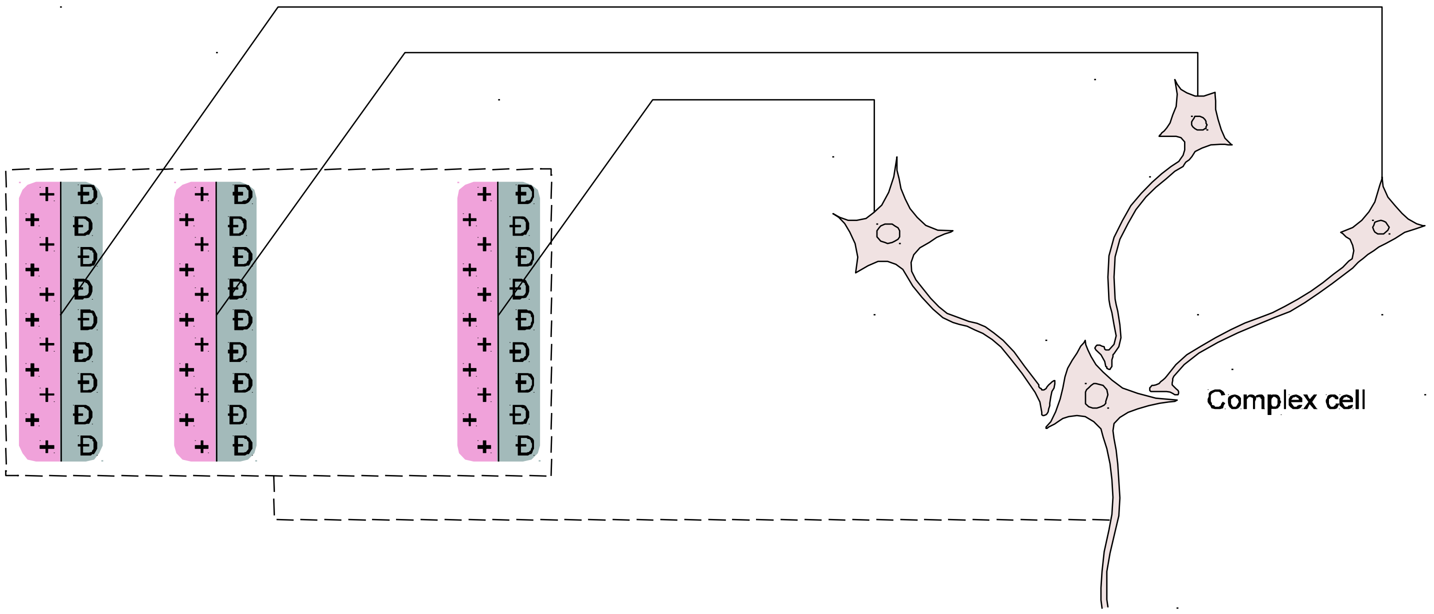


V1 complex cells are sensitive to orientation of stimuli



Adapted from Michael E. Goldberg, M.D.

Complex cells can be constructed from an array of similarly oriented simple cells



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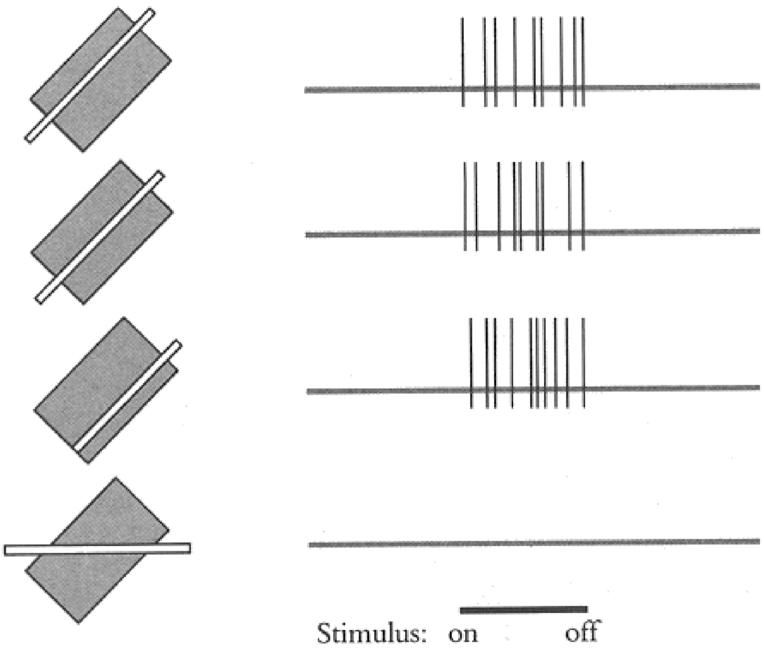
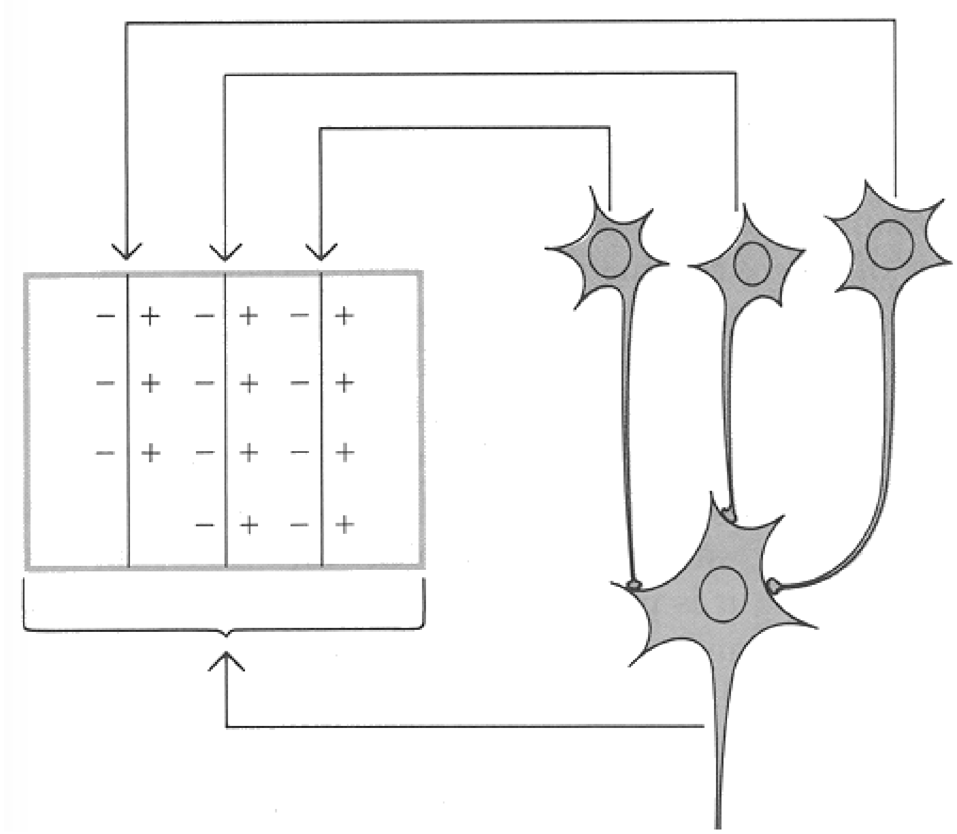
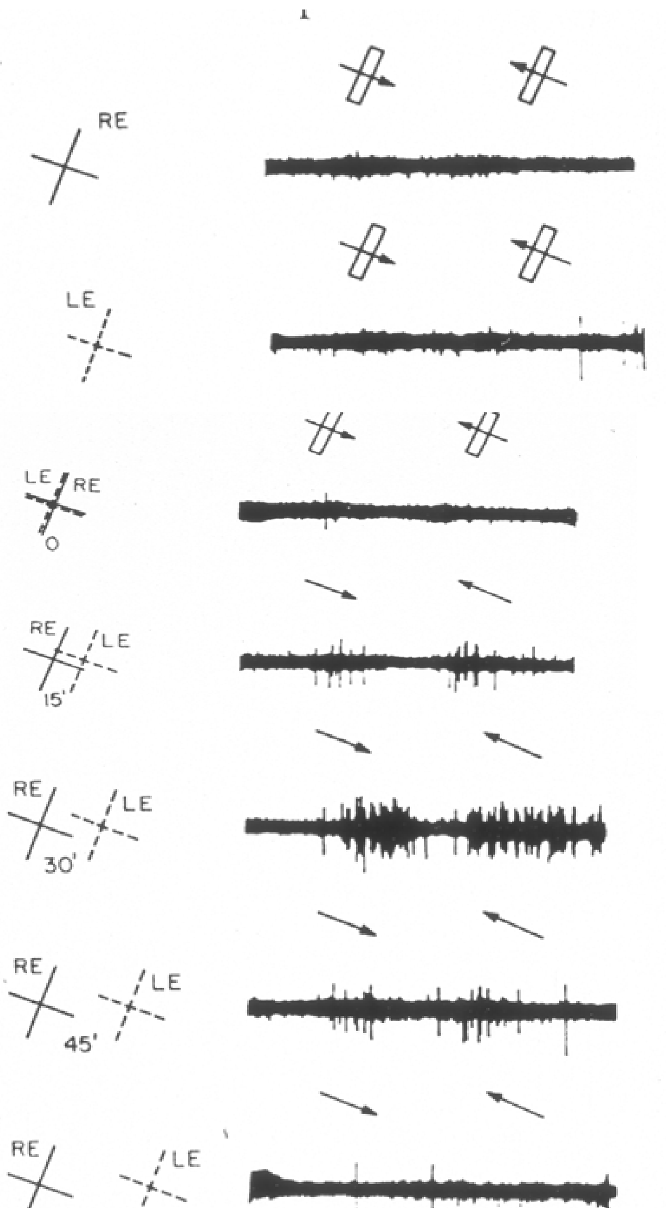
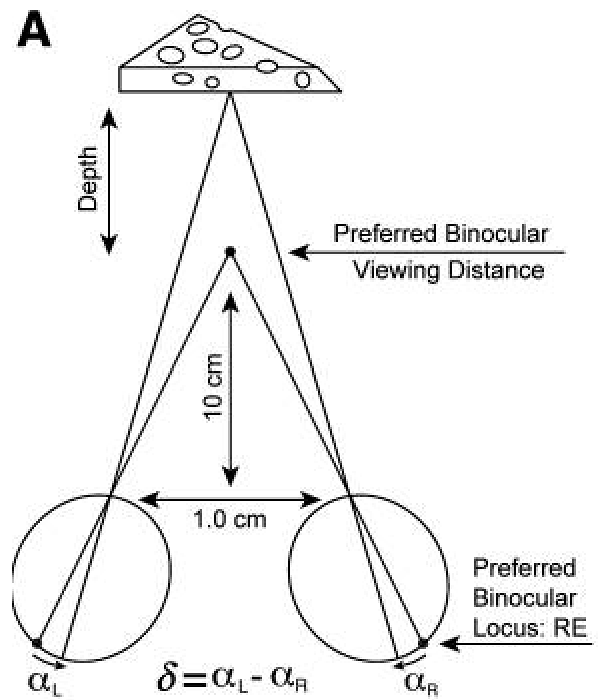
V1 complex cells are sensitive to orientation of stimuli

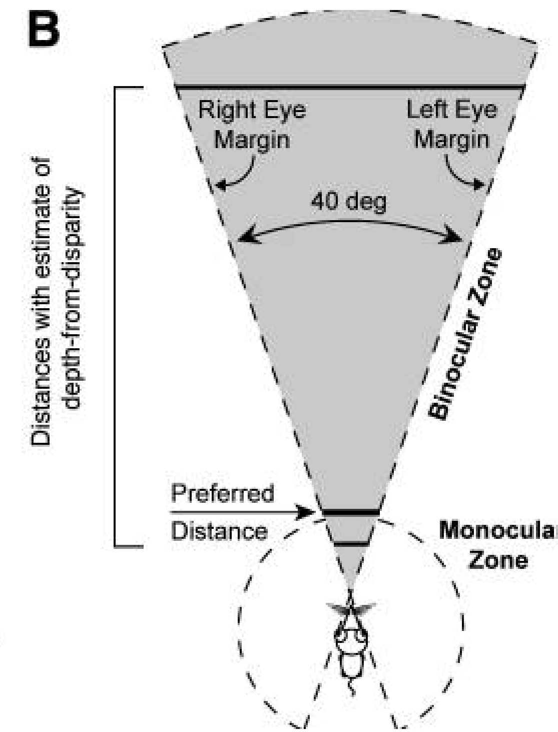




Disparity selectivity in a V1 neuron

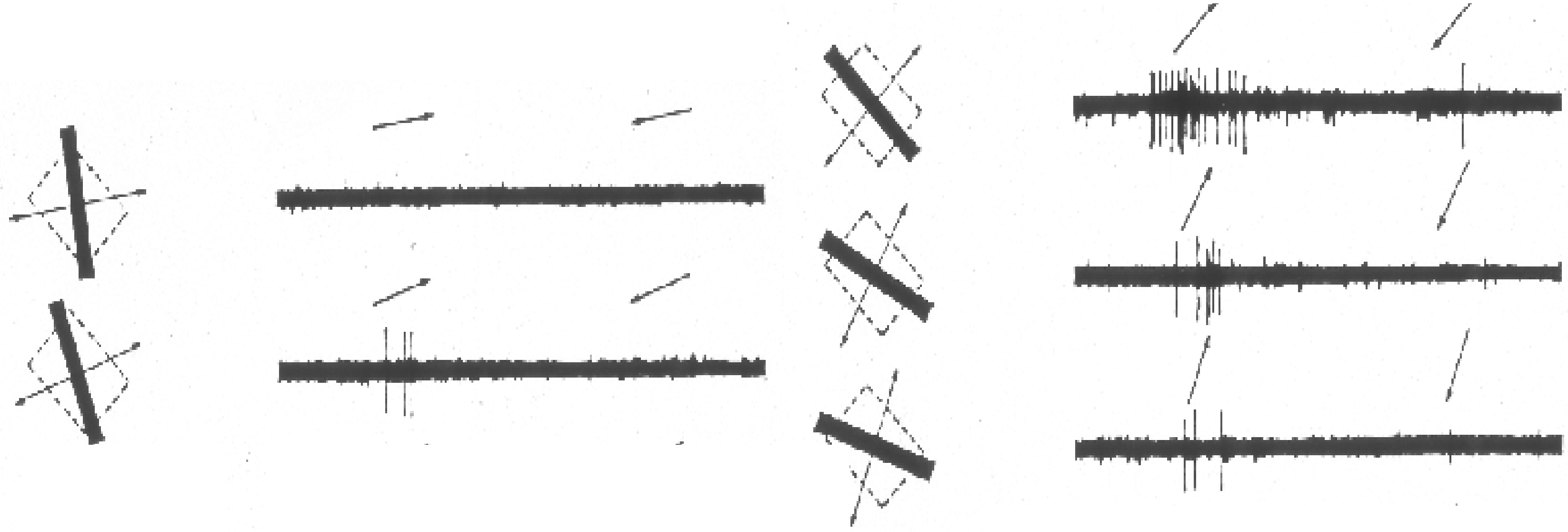






Adapted from Michael E. Goldberg, M.D.

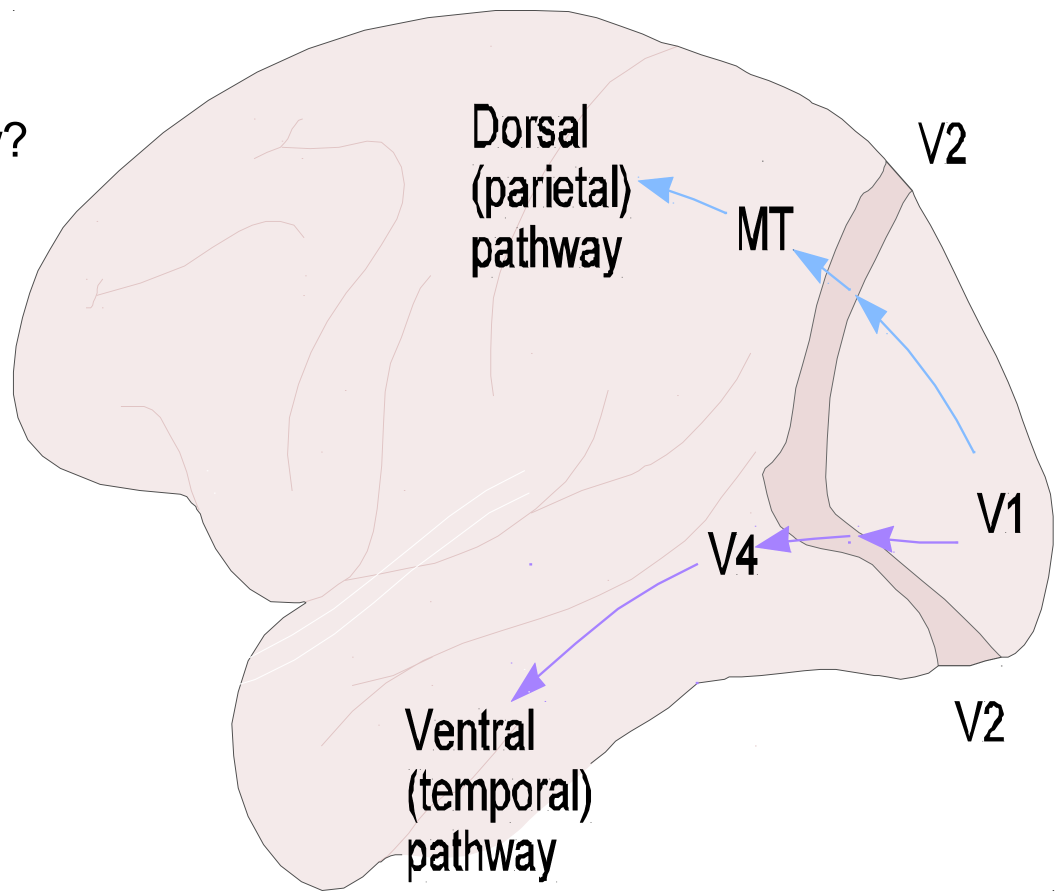
Motion selectivity in a V1 neuron



Adapted from Michael E. Goldberg, M.D.

Two cortical visual streams subserve two different visual functions.

Where/how?



What

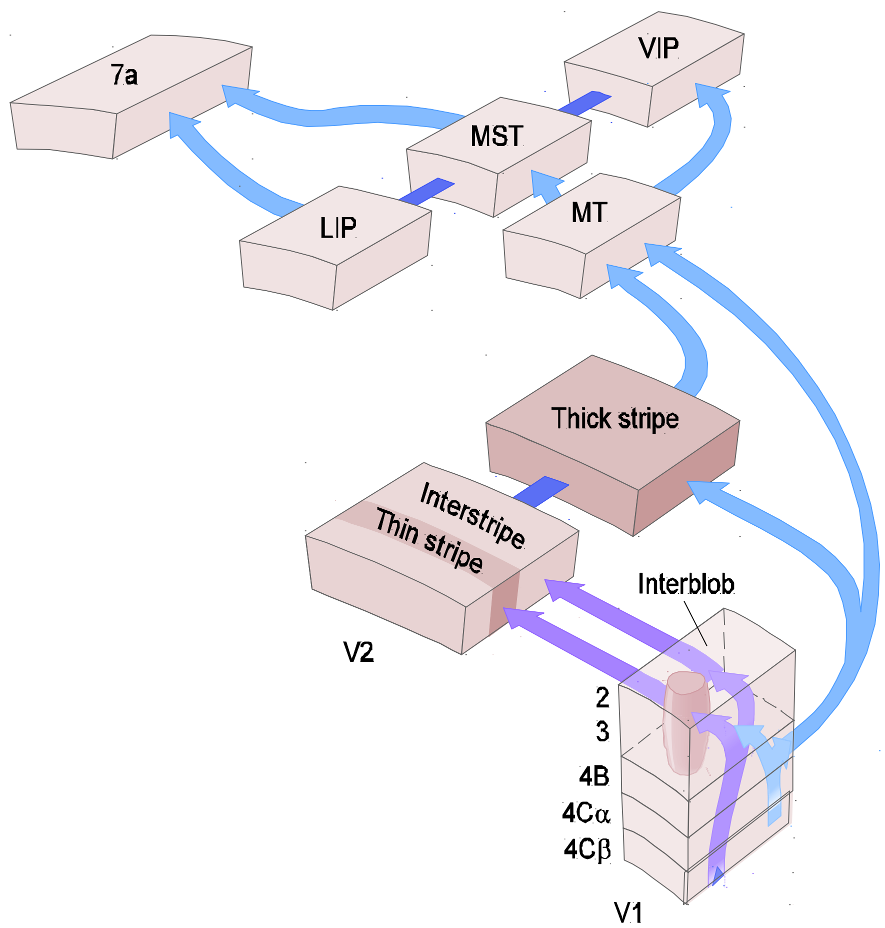
Adapted from Michael E. Goldberg, M.D.

Patients demonstrate this functional segregation

- Patients with V1 lesions generally have total visual field deficits in the affected field.
- Patients with dorsal stream lesions have deficits in sensory location (and attention), motion perception, color perception, and the performance of visually-guided movements.
- Patients with ventral stream lesions have visual agnosia, the inability to associate a visual stimulus with a name or function.

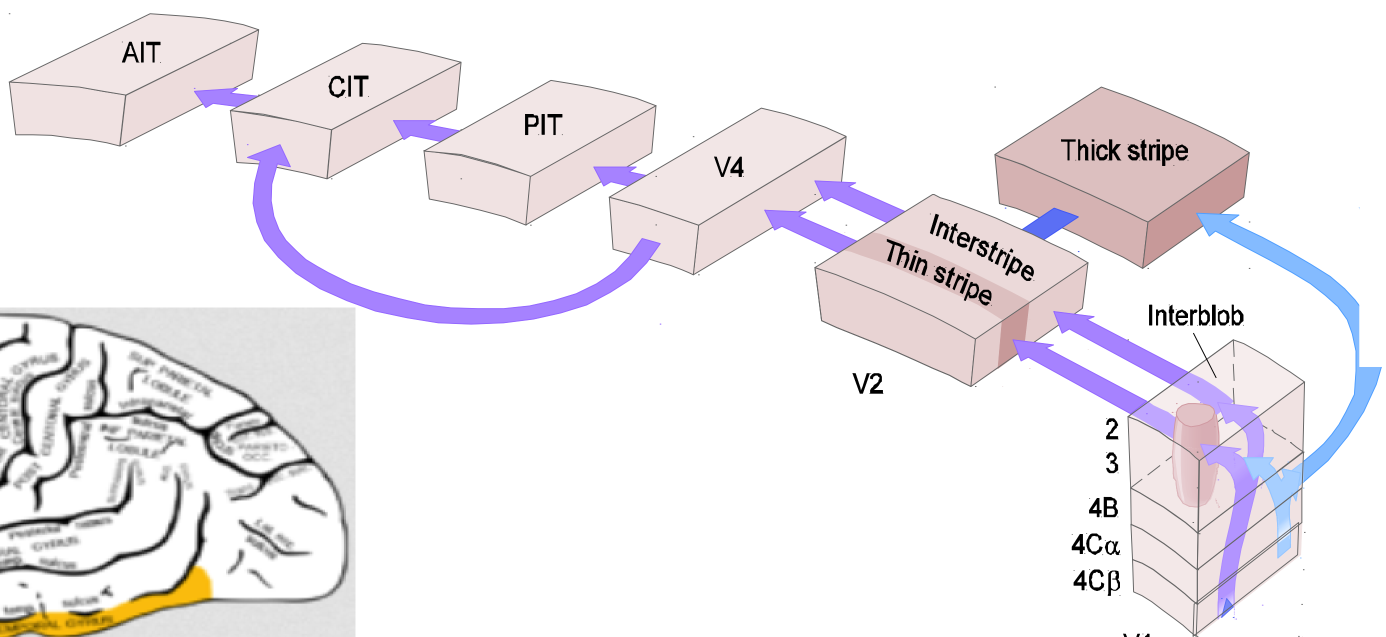
Adapted from Michael E. Goldberg, M.D.

After V2, different functions are performed by anatomically different areas: The dorsal stream provides vision for action –"where and how"



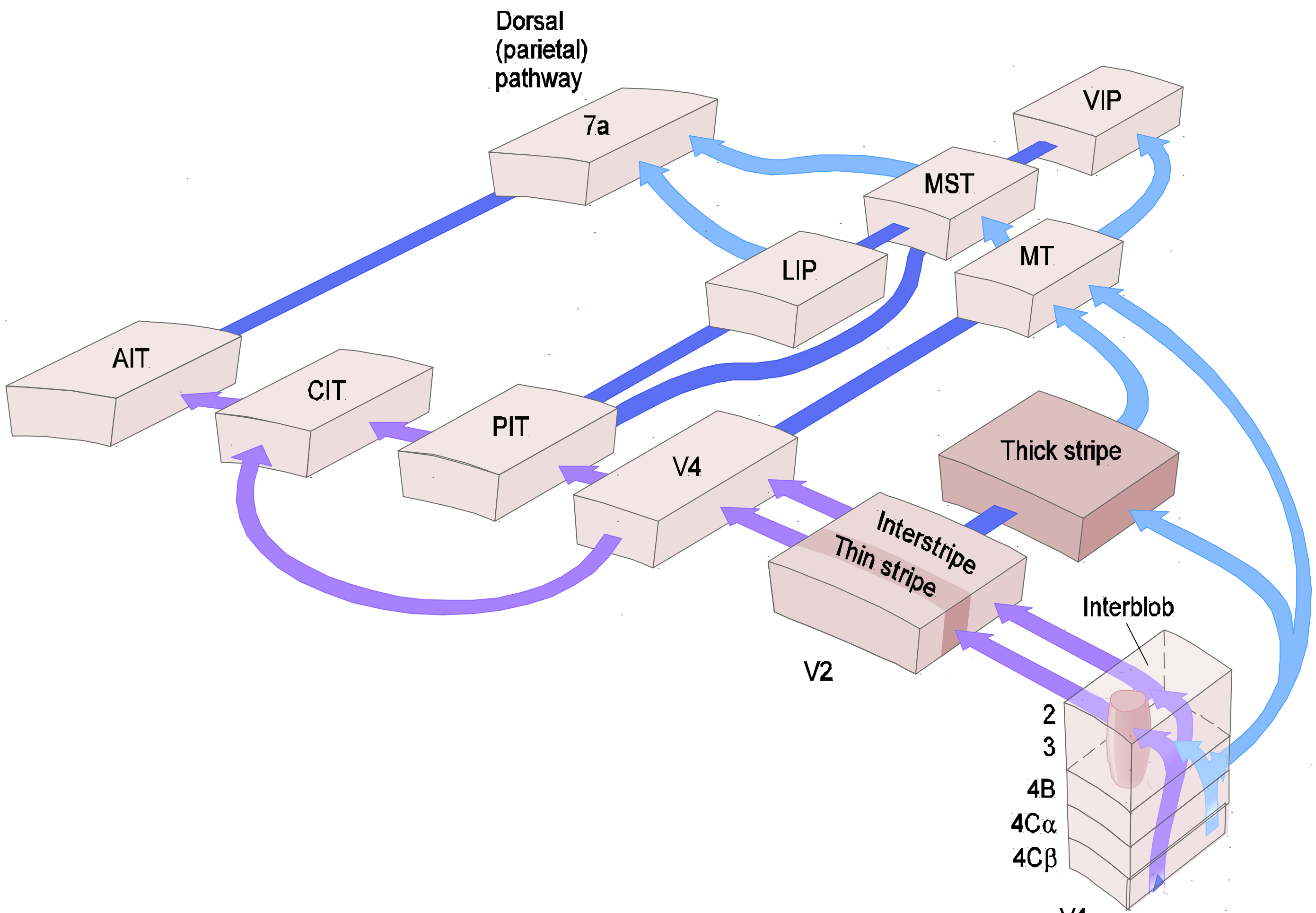
Adapted from Michael E. Goldberg, M.D.

After V2, different functions are performed by anatomically different areas:
The ventral stream provides vision for object identification



Adapted from Michael E. Goldberg, M.D.

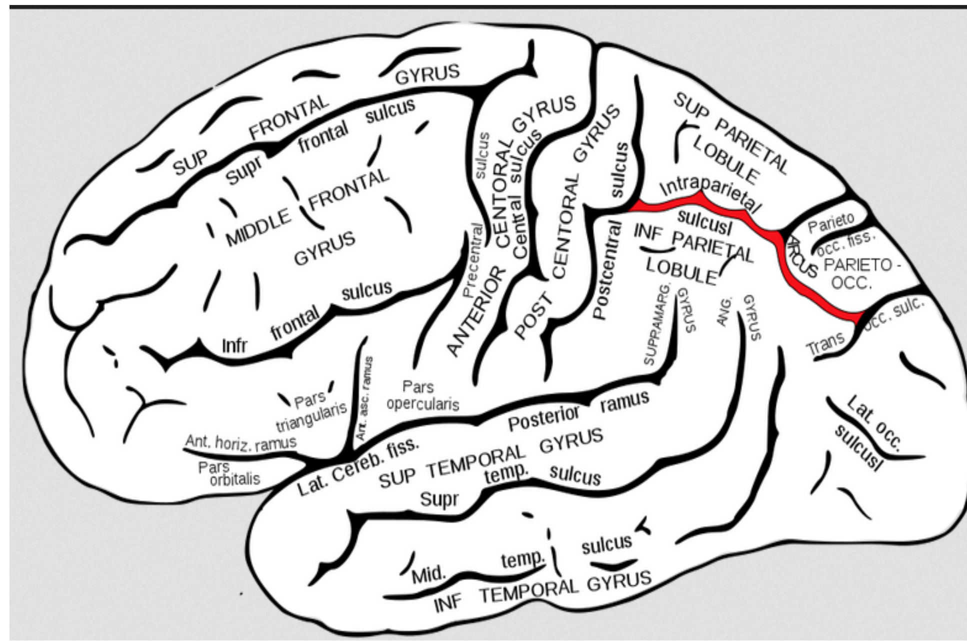
After V2, different functions are performed by anatomically different areas: But the areas are interconnected

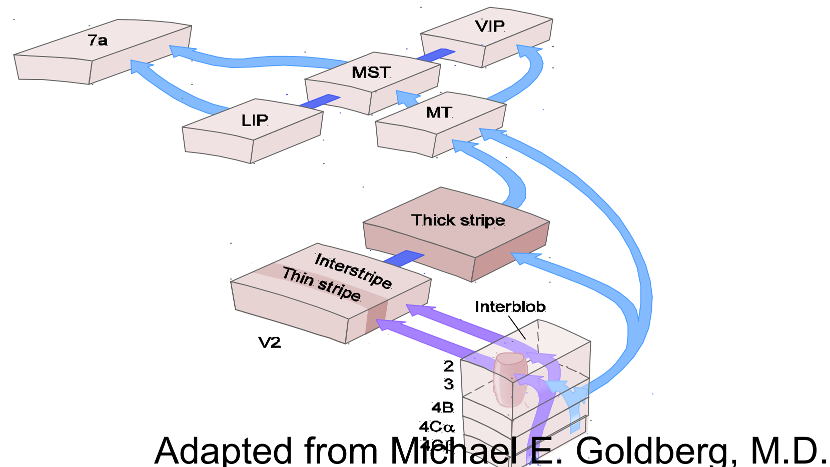


Adapted from Michael E. Goldberg, M.D.

Within the dorsal stream there is further functional segregation –

- MT is specialized for depth and motion.
- LIP is specialized for attention in far space.
- MIP is specialized for providing visual. information for reaching.
- AIP is specialized for providing visual. information for grasping.
- VIP is specialized for providing visual. information for mouth and head movements.





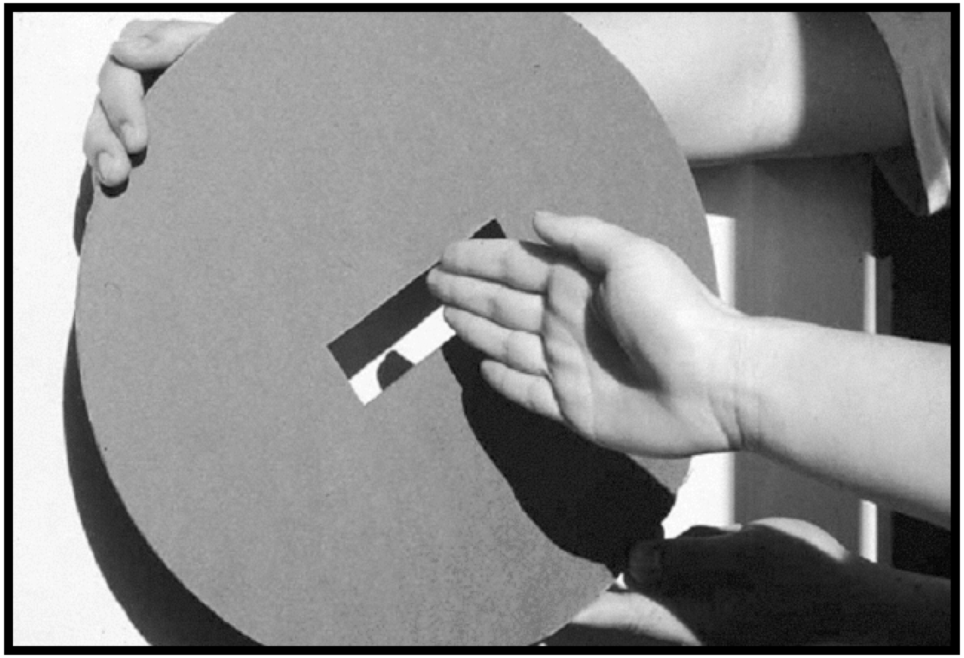
Adapted from Michael E. Goldberg, M.D.

An example of a dorsal stream function

- When you reach for something, your grip opens to accommodate the size of your target.
- Patients with dorsal stream lesions can't do this.
- They can, however, describe the size of the object.

Adapted from Michael E. Goldberg, M.D.

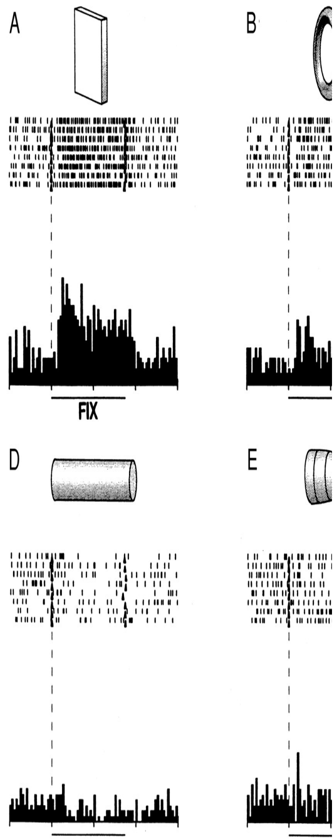
A patient with a dorsal stream lesion cannot orient her hand with respect to a slot

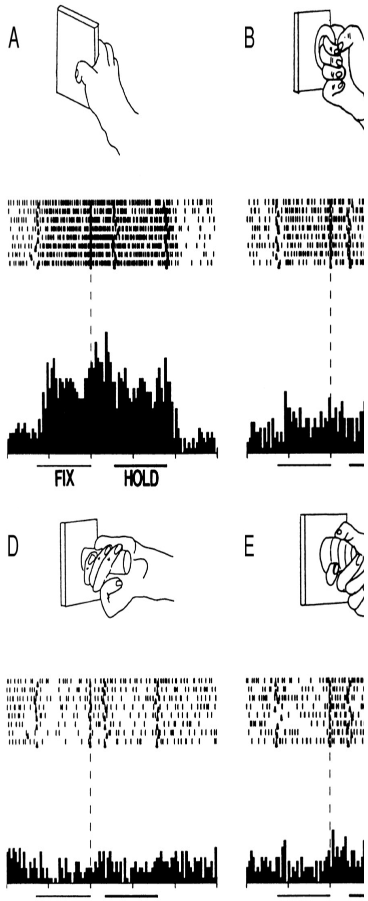


Adapted from Michael E. Goldberg, M.D.

Neurons in AIP specialized for grip

Look at the object



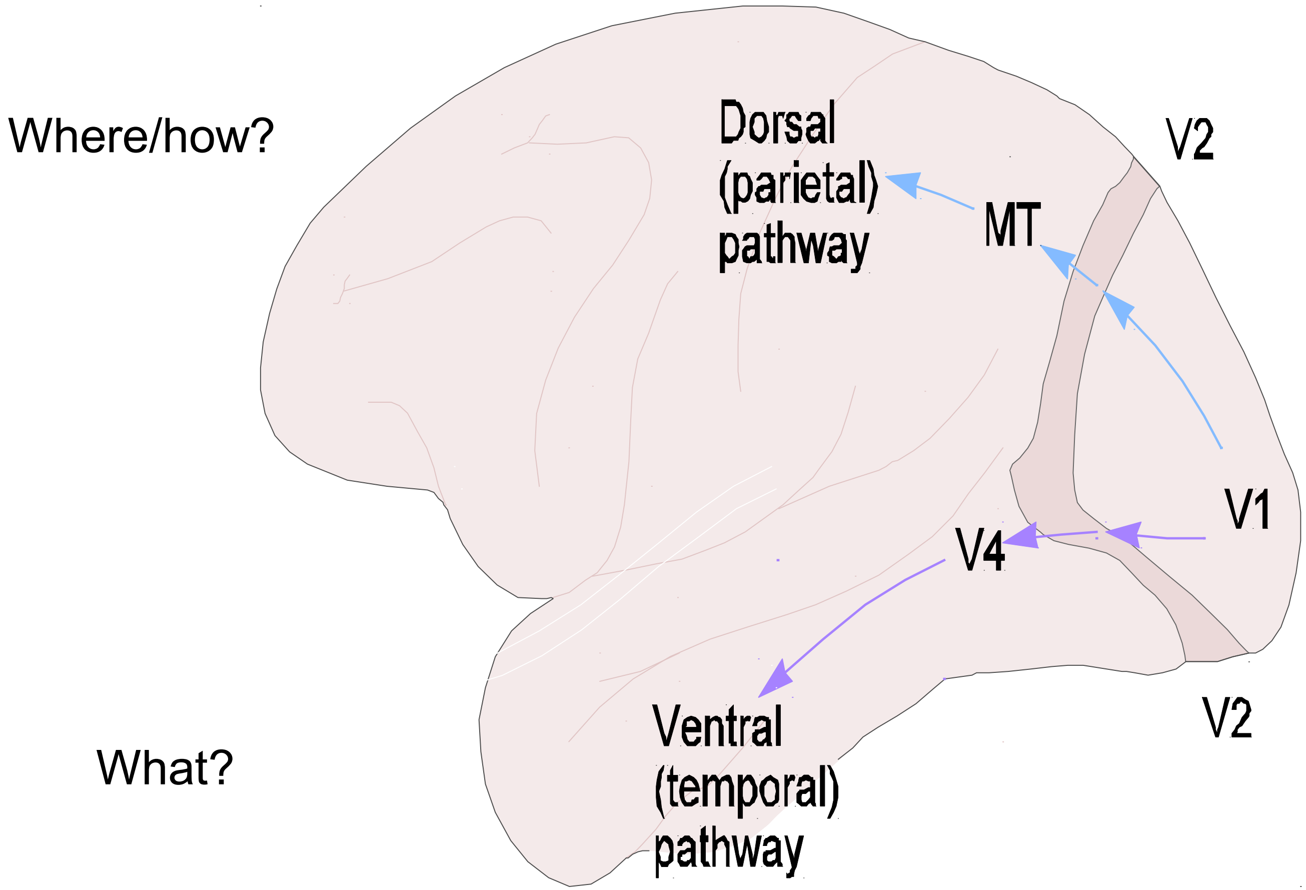


Reach for the object

Dorsal visual pathway is concerned with the aspect of form, orientation, and/or size perception that is relevant for the visual control of movements.

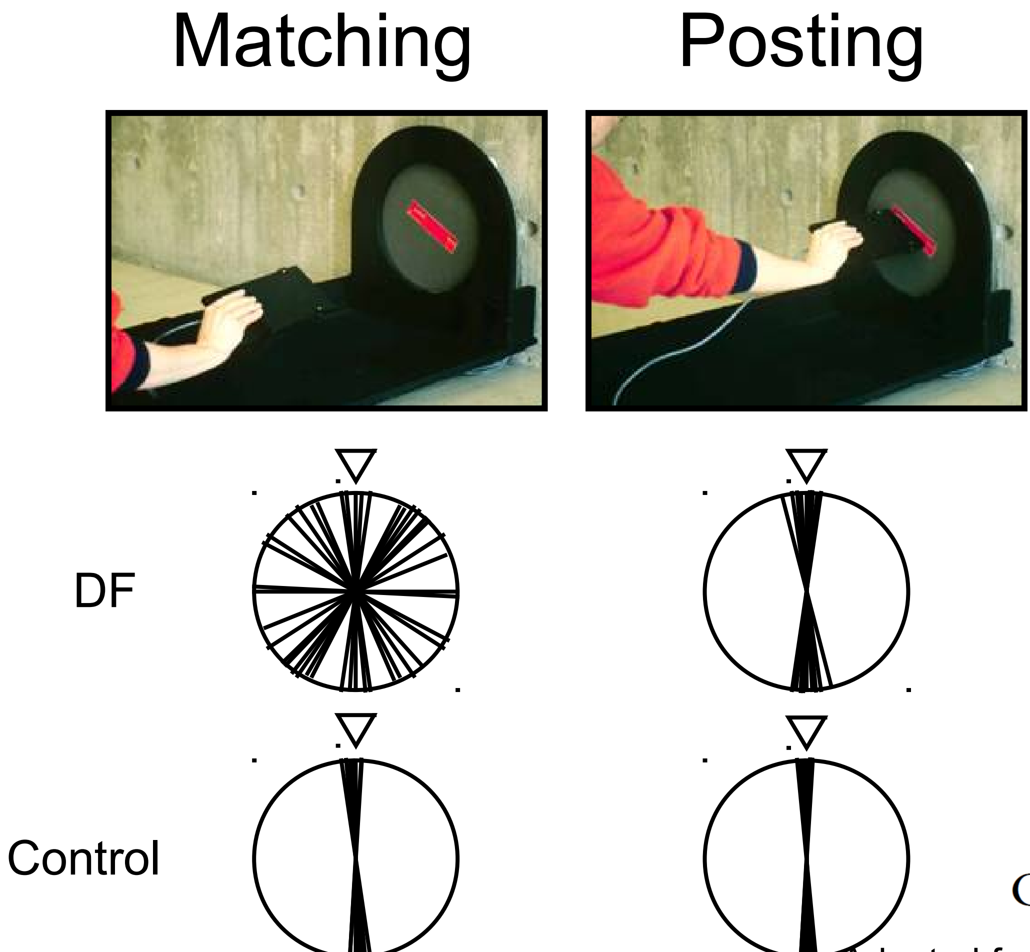
Selectivity for the Shape, Size, and Orientation of Objects for Grasping in Neurons of Monkey Parietal Area AIP Akira Murata, Vittorio Gallese, Giuseppe Luppino, Masakazu Kaseda, Hideo Sakata Journal of Neurophysiology Published 1 May 2000 Vol. 83 no. 5, 2580-2601

The inferior temporal lobe describes the visual world for object recognition



Adapted from Michael E. Goldberg, M.D.

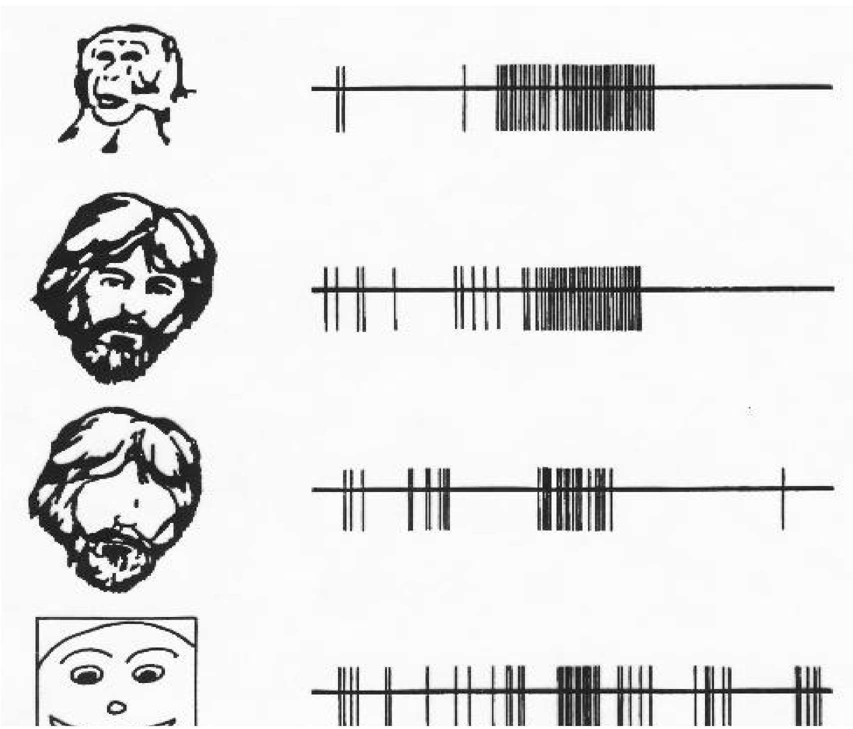
A patient with a ventral stream lesion can move her hand to a slot, but can't match the position or can't report the orientation

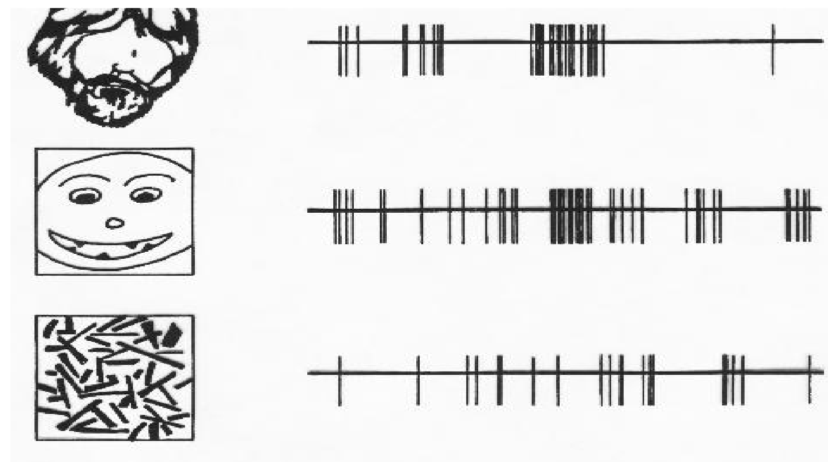


Goodale, et al., (1991)

Adapted from Michael E. Goldberg, M.D.

Neurons in inferior temporal cortex are selective for complex patterns like faces

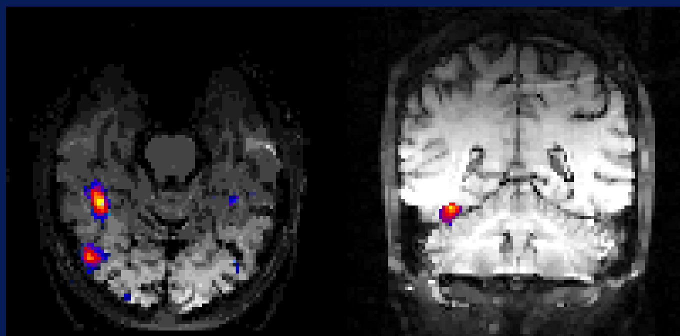


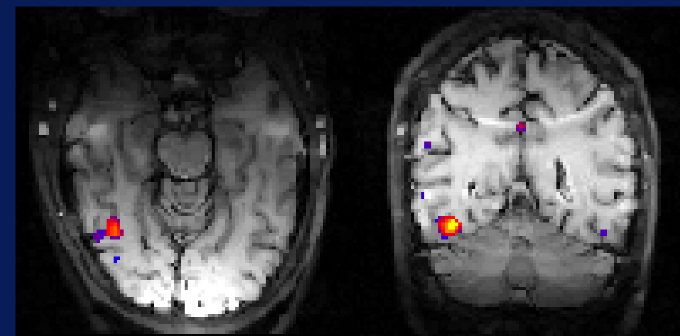


Adapted from Michael E. Goldberg, M.D.

The Fusiform Face Area (FFA)

Kanwisher, McDermott, & Chun (1997)



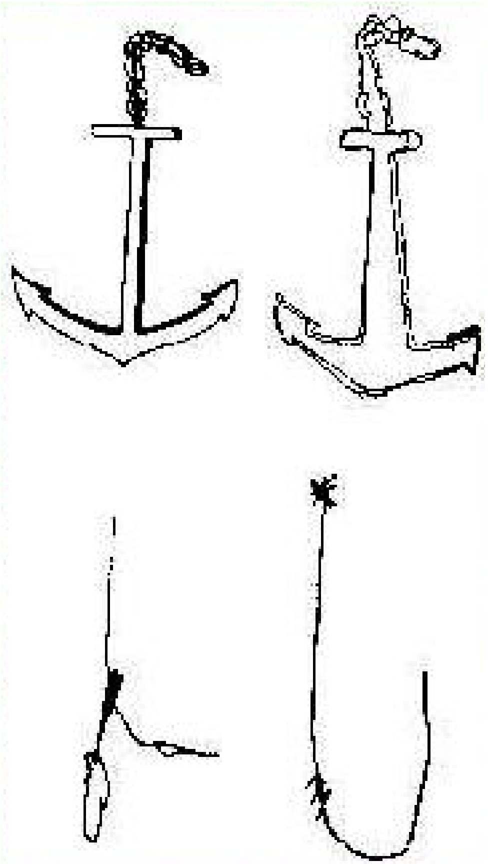


- Responds during passive viewing of faces > objects.
- Cannot be explained in terms of
  - differences in low-level features
  - attentional confounds
  - subordinate - level categorization of any stimulus class
  - generalized response to anything animate/human
- Is selectively involved in perception of faces.

Adapted from Michael E. Goldberg, M.D.

Patients with inferior temporal lesions have visual agnosia

Copy the drawing
Visuomotor function
Intact – but patient
can't name the object



Draw an anchor.
Patient cannot
conceptualize the
anchor

Adapted from Michael E. Goldberg, M.D.

Ventral stream patients

- Cannot identify objects
- But they can make appropriate visually-guided movements.
- The patient who could not set her grip can still tell you which cylinder is thicker.
- The patient who cannot tell you which cylinder is thicker can set still her grip.

Adapted from Michael E. Goldberg, M.D.

Prosopagnosia “face blindness” is the most dramatic ventral stream deficit

- Term first used by Bodamer, 1947
- Inability to recognize familiar faces
- Visual acuity is normal
- Caused by lesion to right inferior temporal lobe
- May be congenital (“developmental prosopagnosia”)
- Patients compensate by using other recognition cues: clothing, gait, voice, etc.

Adapted from Michael E. Goldberg, M.D.