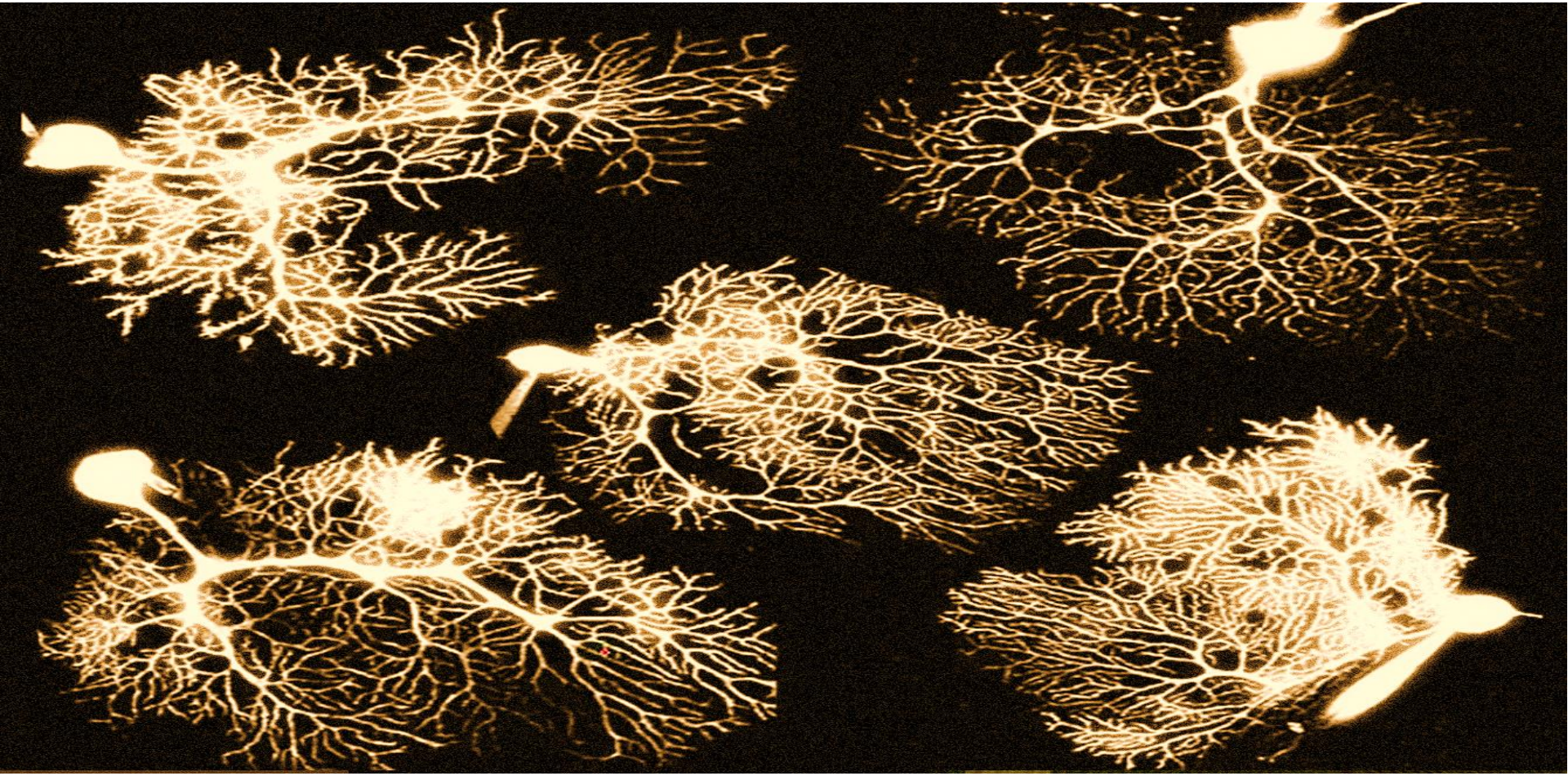
Neuroscience of Learning, Memory, Cognition

Part I: Neuronal Networks



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Neuron Models

Set I

Outline

- Sensing & perception
- Neurons & spikes
- The Hudgkin-Huxley equation
- Modeling neuronal dynamics

Some slides credit:

- Adrienne Fairhall, Rajesh Rao, UW course material 2013-2017
- Wulfram Gerstner, EPFL course material 2018

Other credits as noted on slides

Cover slide drawing: Santiago Ramon Y Cajal

Textbooks:

- Peter Dayan & Larry Abbott “Theoretical Neuroscience”, 2005
- Wulfram Gerstner “Neuronal Dynamics”, 2014
- Eugene Izhikevich “Dynamical Systems in Neuroscience”, 2010

Reference book:

- Paul Miller “An Introductory Course in Computational Neuroscience”, 2018

Outline

- Sensing & perception
  - Neurons in the brain
  - Visual cortex & receptive fields
  - Vision & perception
- Neurons & spikes
  - Electrical personality of a neuron
  - Ionic channels
  - Action potential
- The Hudgkin-Huxley equation
  - The passive membrane
  - Voltage-gated channels
  - Anatomy of a spike
- Neuronal dynamics
  - Phase portrait models
  - Fixed points and their stability
  - Bifurcation (saddle-node / Hopf)
  - Simplified 2D models

Neurons in The Brain

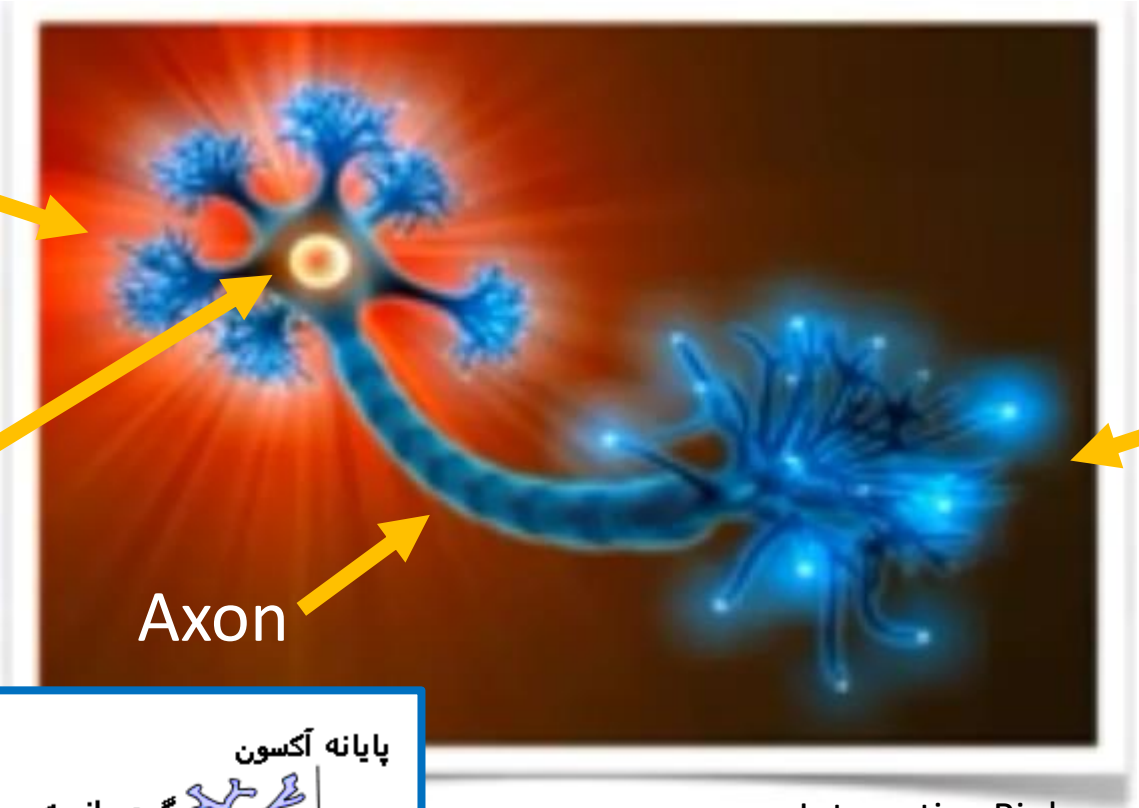
Neurons

Dendrites

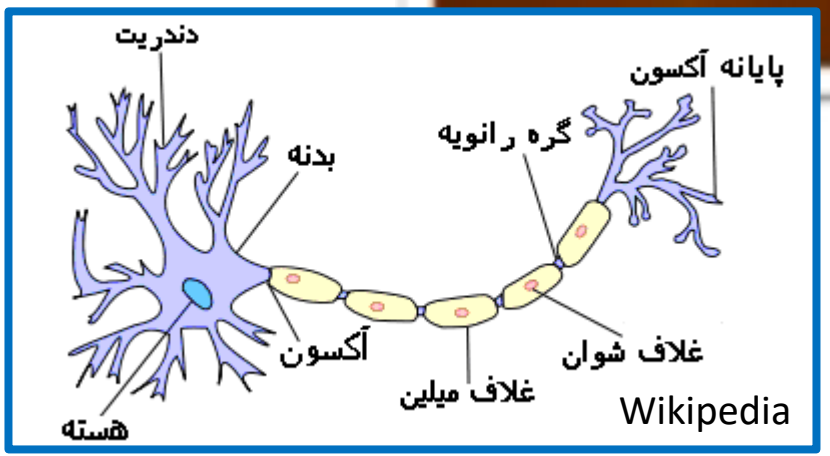
Soma / Cell Body

Axon

Axon Terminals



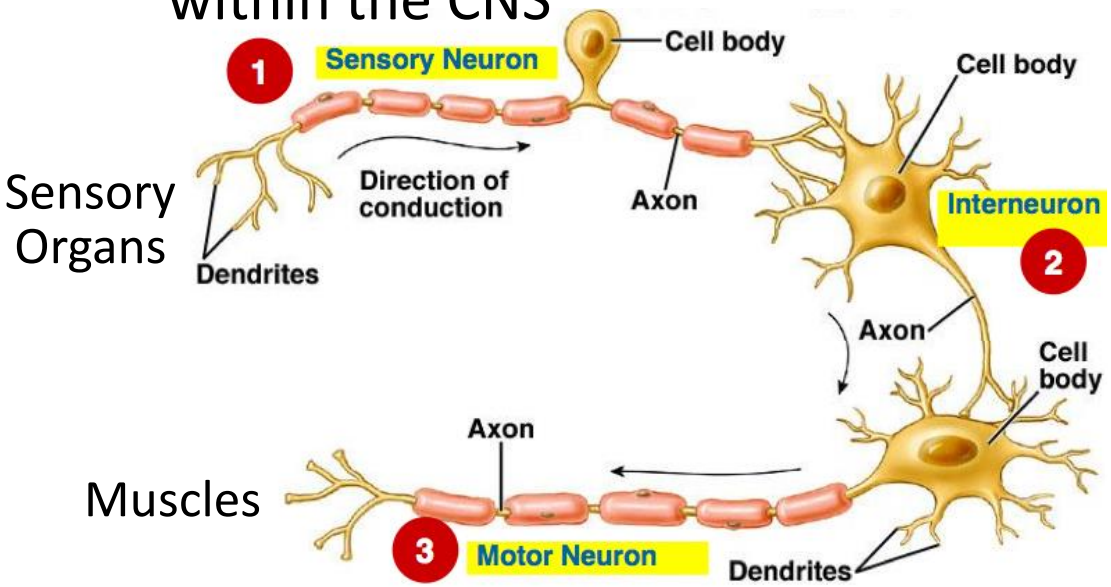
Interactive Biology

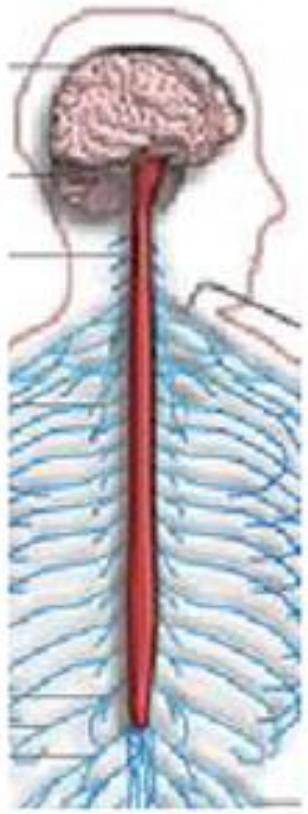


Wikipedia

Neurons

- Three types of neurons:
  - ***Sensory neurons:*** Send signals TO the CNS (Central Nervous System)
  - ***Motor neurons:*** Send signals AWAY from the CNS
  - ***Interneurons:*** Processing & transmission within the CNS





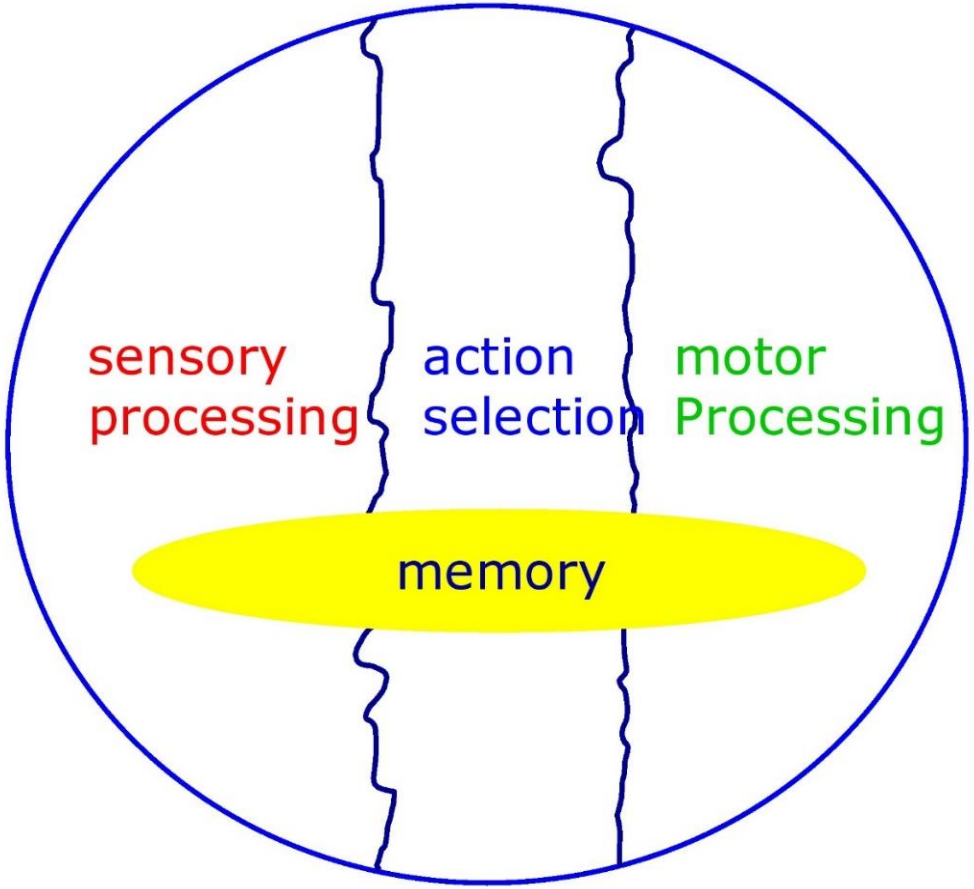
CNS

(Central Nervous System)

= Brain + Spinal Cord

The Brain

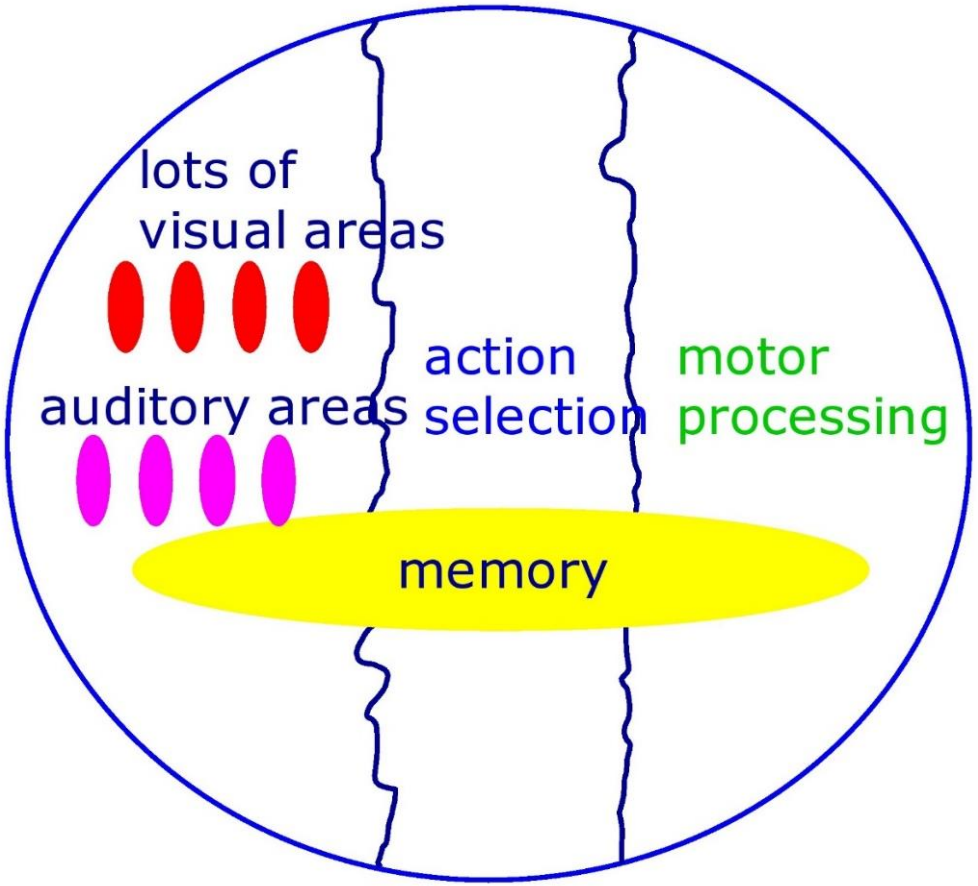
Structure at the macroscopic level



from Gatsby Computational Neuroscience course

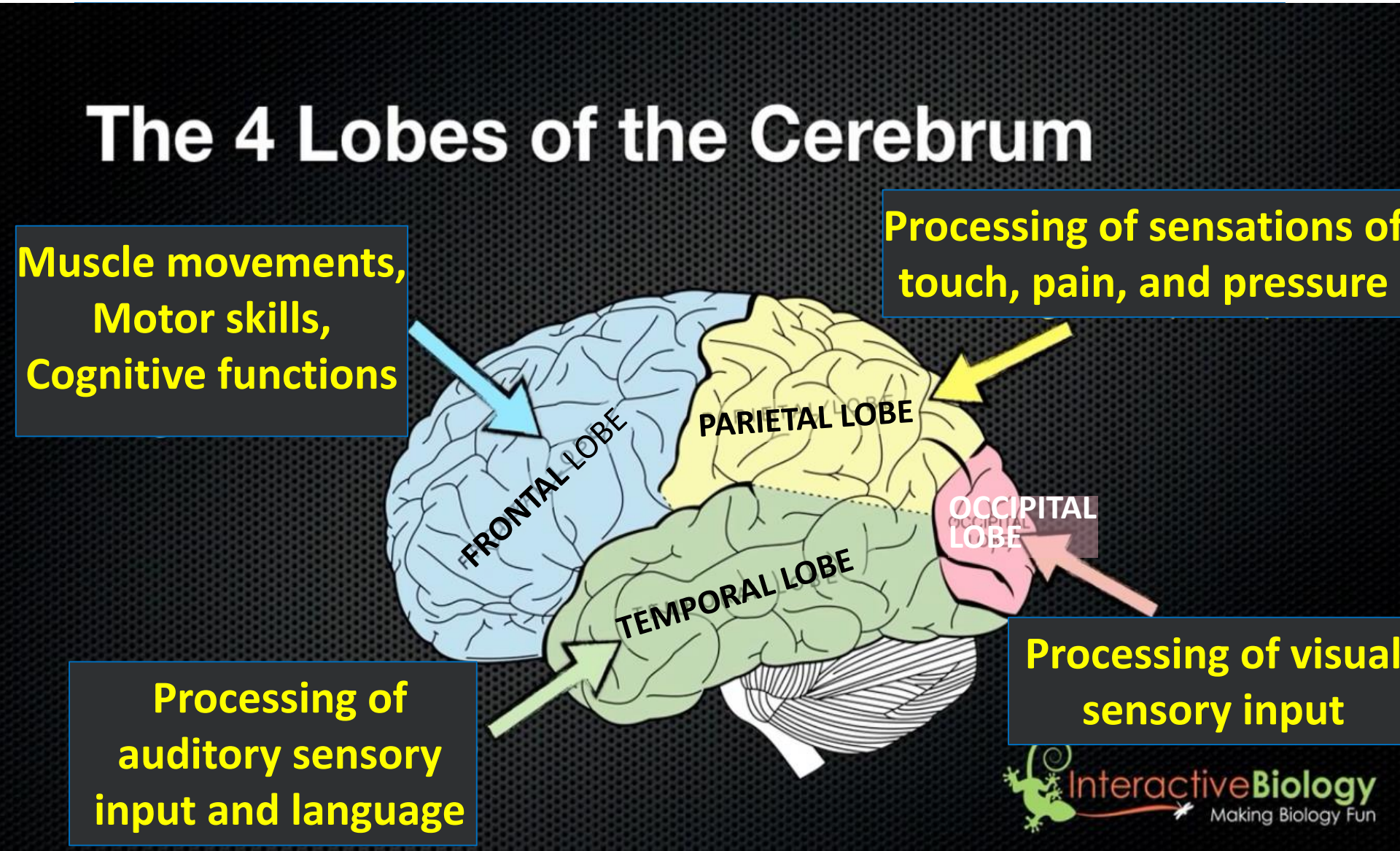
The Brain

Structure at the macroscopic level

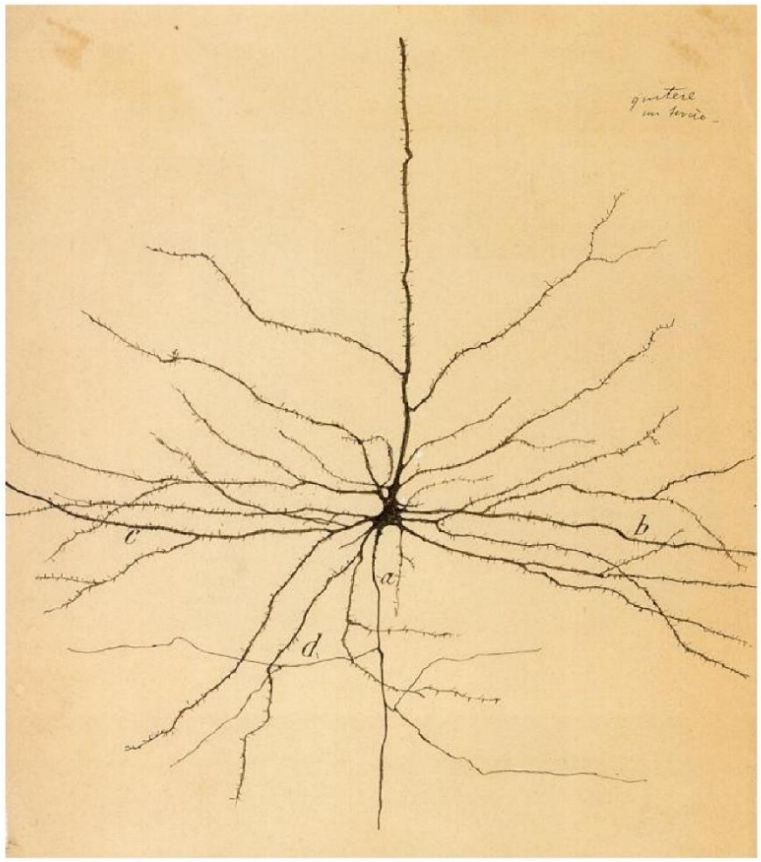


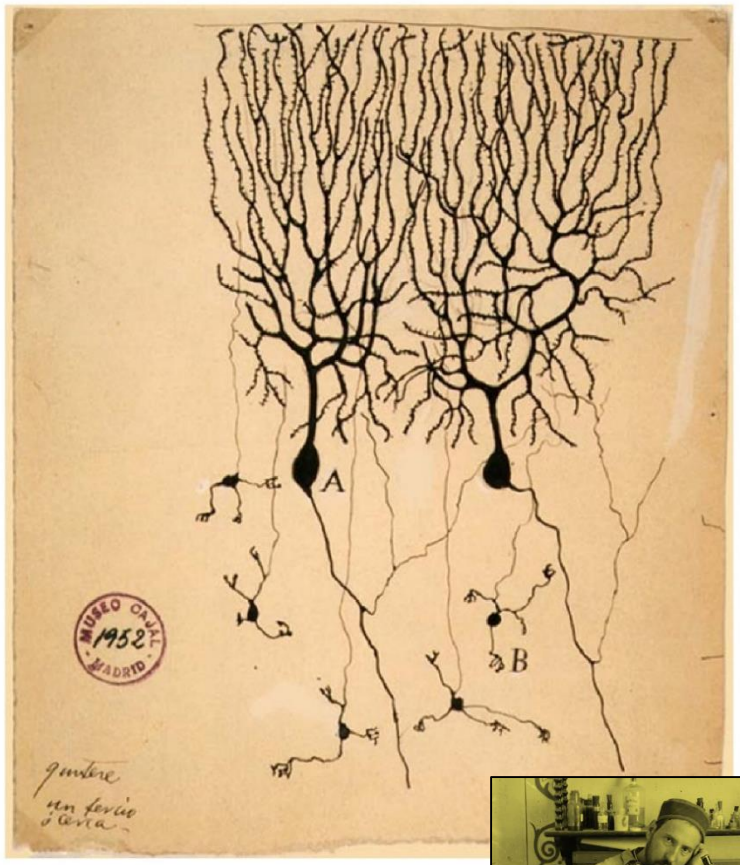
from Gatsby Computational Neuroscience course

The Brain


The 4 Lobes of the Cerebrum
Muscle movements, Motor skills, Cognitive functions
Processing of sensations of touch, pain, and pressure
FRONTAL LOBE
PARIETAL LOBE
OCCIPITAL LOBE
TEMPORAL LOBE
Processing of auditory sensory input and language
Processing of visual sensory input
InteractiveBiology
Making Biology Fun

Neurons in The Brain





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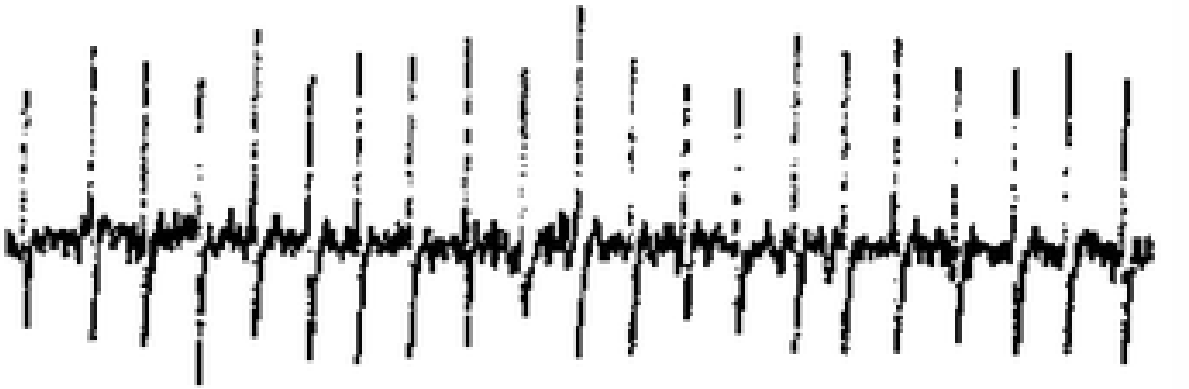
Santiago Ramón y Cajal (drawn 1899)

How many neurons are in the human brain?

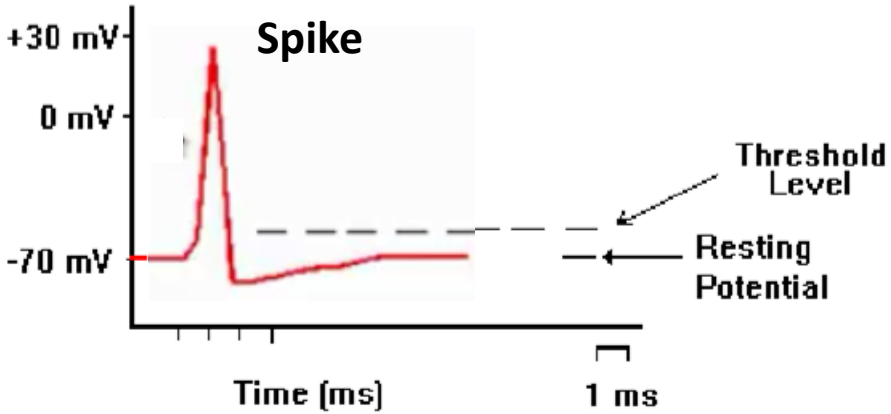
Neurons in The Brain

Brain (1.5 Kg)	**CPU**
10^{11} neurons	10^{9} transistors
10^{14} connections (>1000 connections / neuron, for some up to 10,000 connections)	10^{9} connections (few connections / transistor)
8 million Km of axons	2 Km of wire

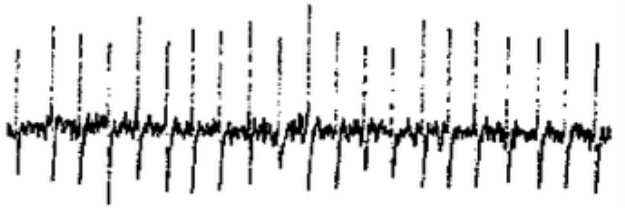
Neurons in The Brain

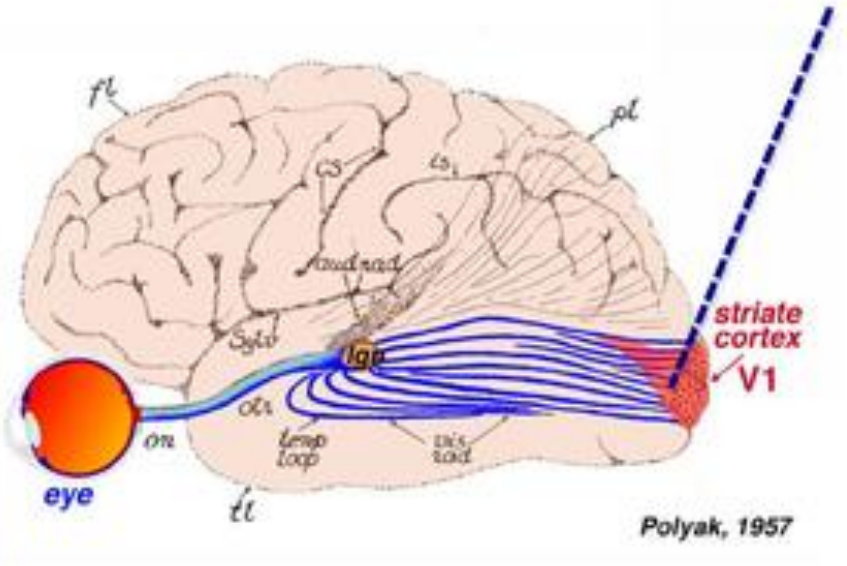


Spike (action potential): Approximately 100 mV rise in voltage, lasting for approximately 1 msec



Neurons in The Brain

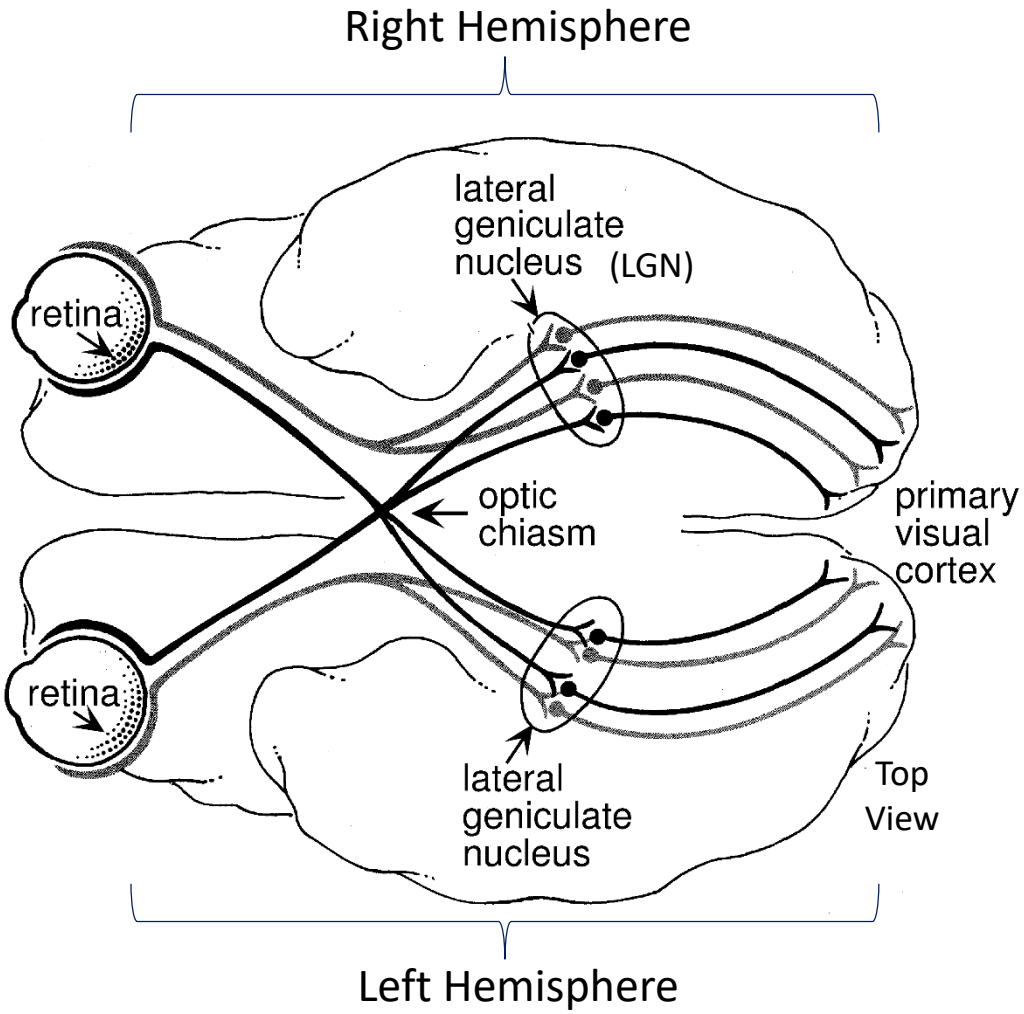


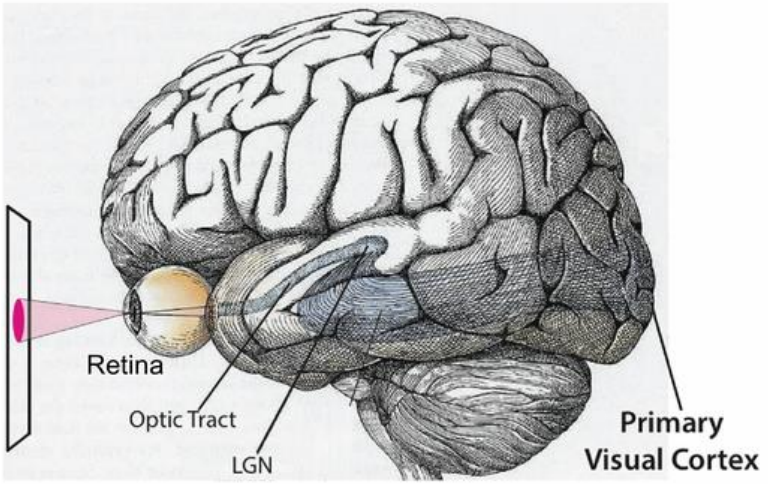


Example: Visual neurons spike in response to features or properties of images

Visual Cortex & Receptive Fields

The Visual System –
Visual Data Pathways





From Hubel

Dayan and Abbott, *Theoretical Neuroscience* Book, 2005

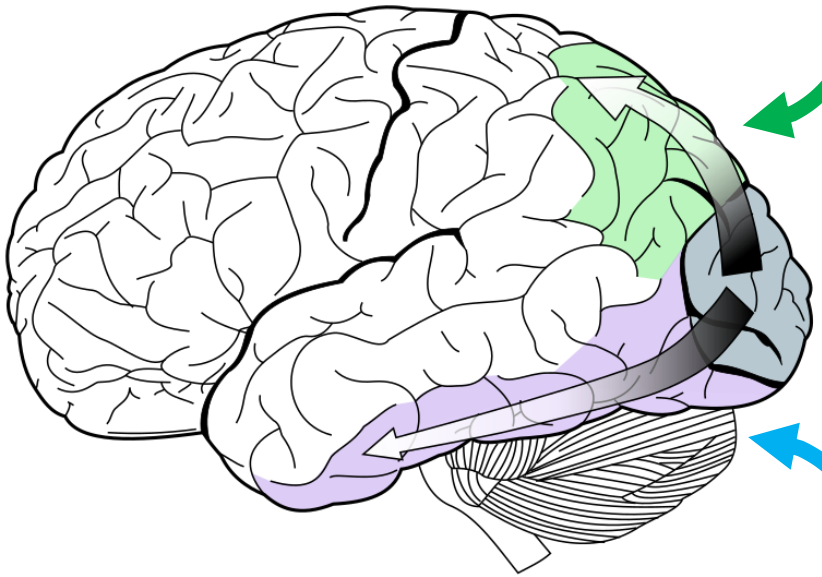
The Visual System –
Visual Processing Pathways

- V1 transmits information to two primary pathways, called the *ventral stream* and the *dorsal stream*

Dorsal stream:

The "Where or How" Pathway

- Motion
- Object locations
- Control of the eyes and arms (especially when visual information is used to guide saccades or reaching)



Primary visual cortex (V1)

Ventral stream:

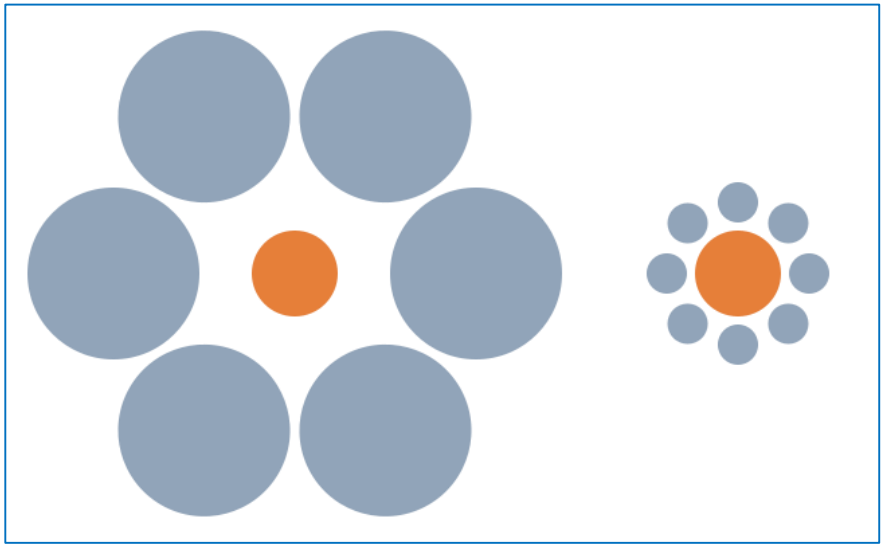
The "What" Pathway

- Form recognition
- Object representation

Wikipedia Commons

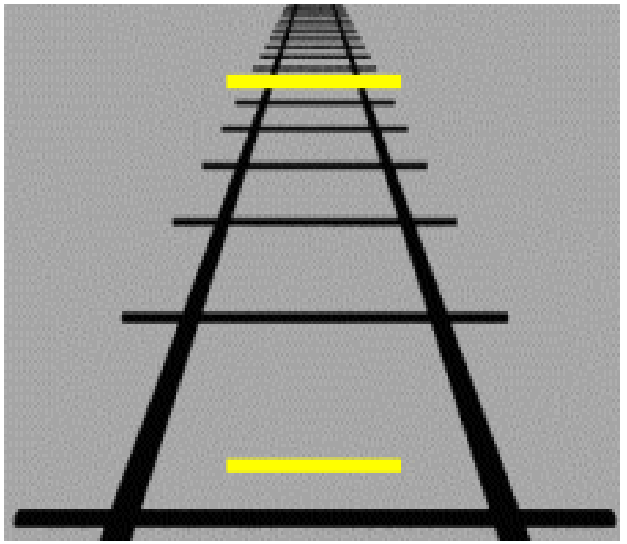
The Visual System –
Visual Processing Pathways

- The ***ventral stream*** is critical for **visual perception** whereas the ***dorsal stream*** mediates the ***visual control*** of skilled actions
- Visual illusions distort judgements of a perceptual nature *(only ventral stream is involved)*
- But when we respond with an action, such as comparing or grasping, no confusion occurs *(when dorsal stream gets involved)*



Ebbinghaus illusion

Wikipedia Commons



Ponzo illusion

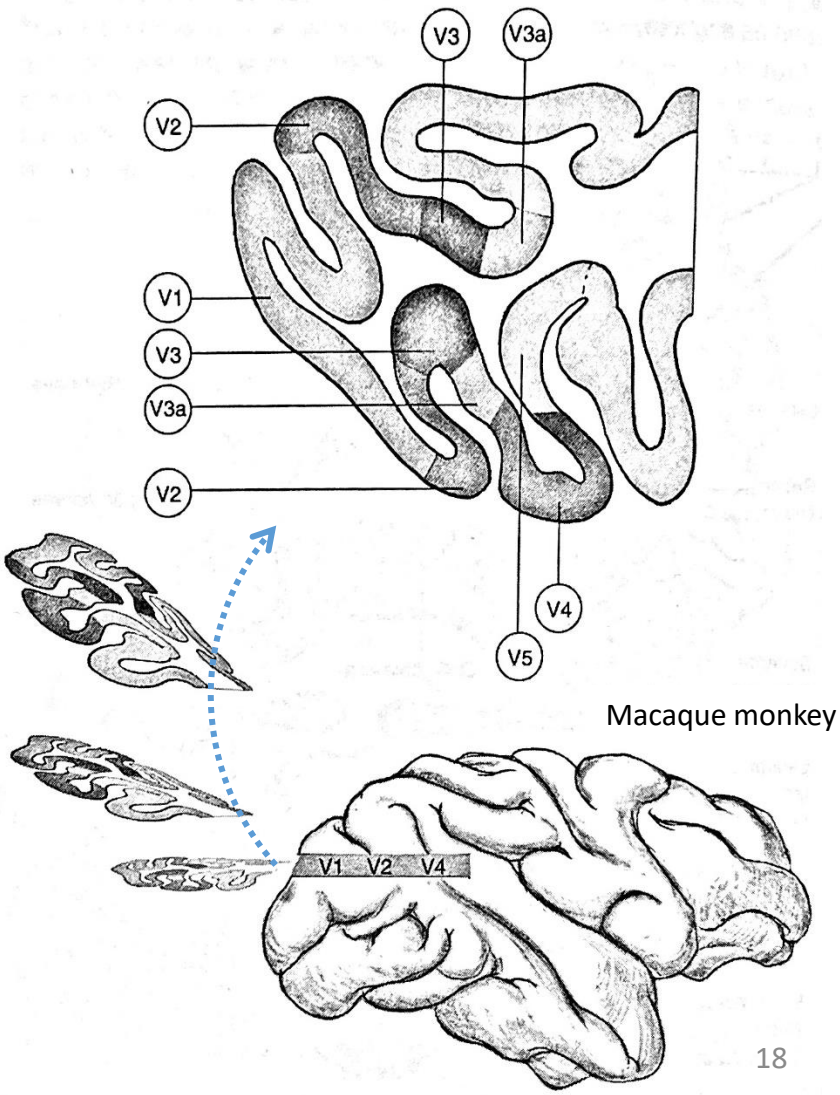
The Visual Cortex –
Processing Layers

- Cells in V1, V2, V3 respond to light ON and OFF, and to lines at particular orientations

  (as we shall see next)

- Cells in V4 respond to specific colors

- Cells in V5 respond to objects moving in particular directions



Macaque monkey brain

Mind and Brain, *A Graphic Guide*, A. Gellatly & O. Zarate

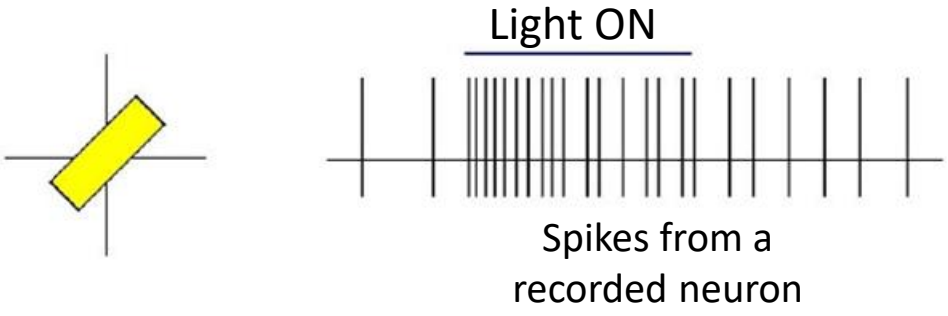
Receptive Fields

Definition:

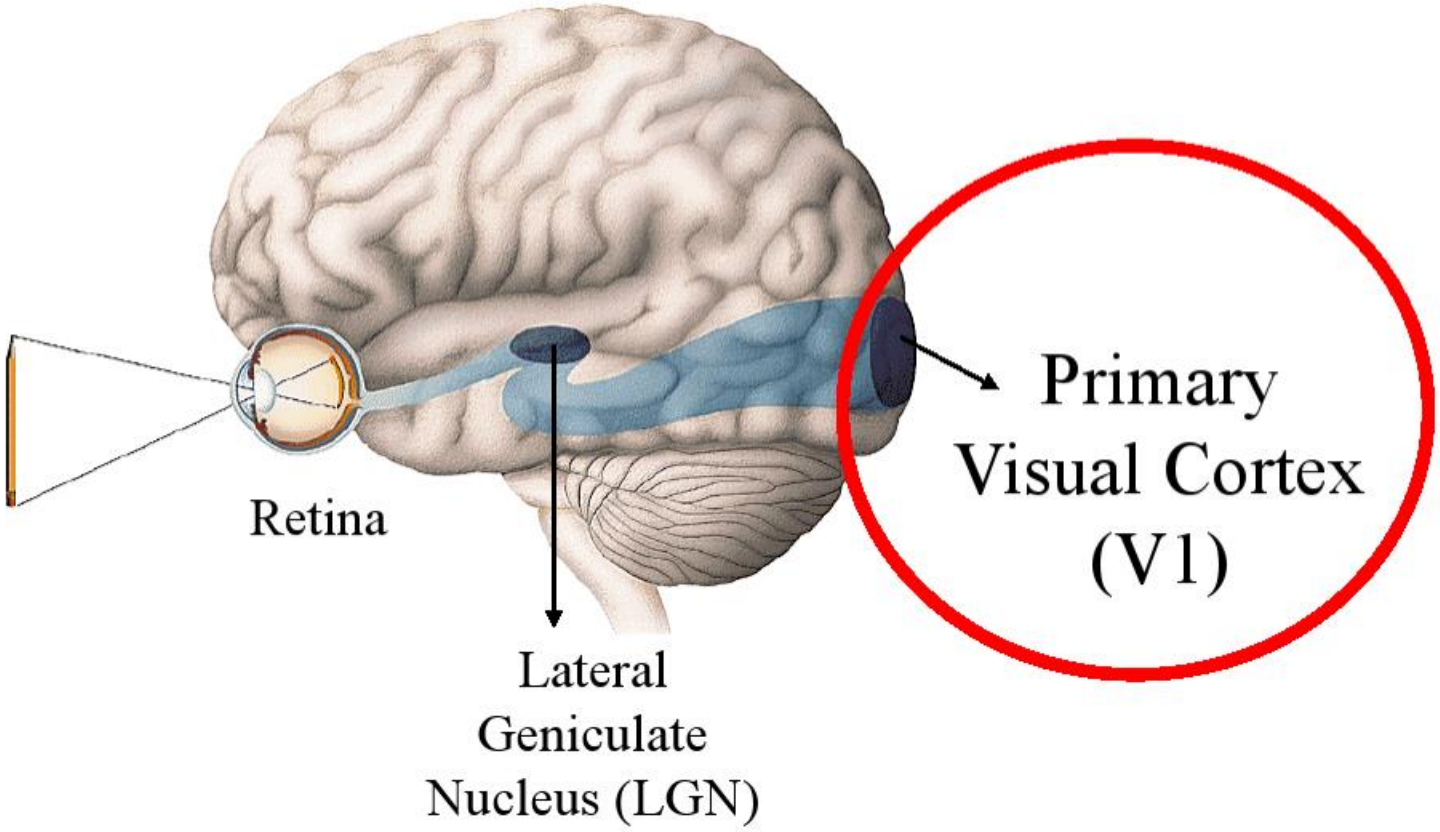
- *Specific properties* of a sensory stimulus that generate a strong response from the cell

Example:

- **A neuron in primary visual cortex turns on when a bar of light at a certain *orientation* and *location* is in the field of view**

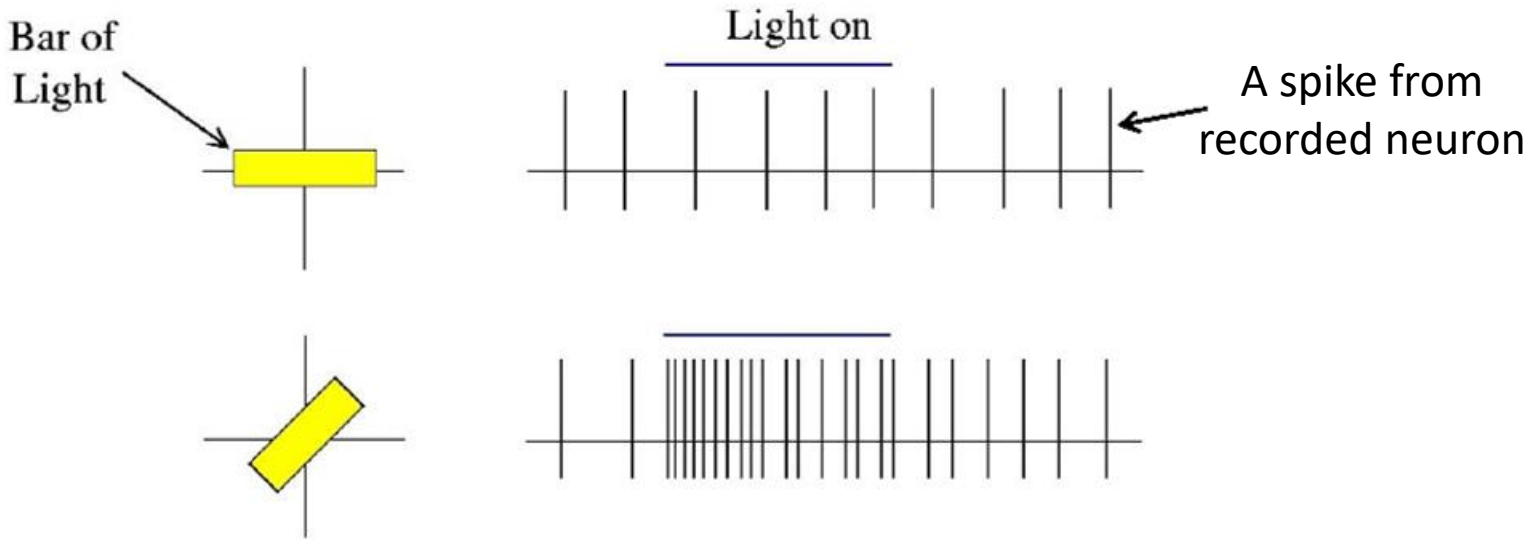


Receptive Fields – Visual Cortex V1



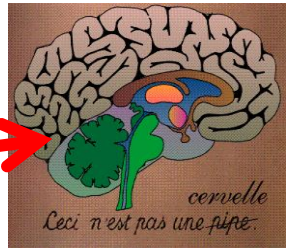
Let's look at receptive fields in V1

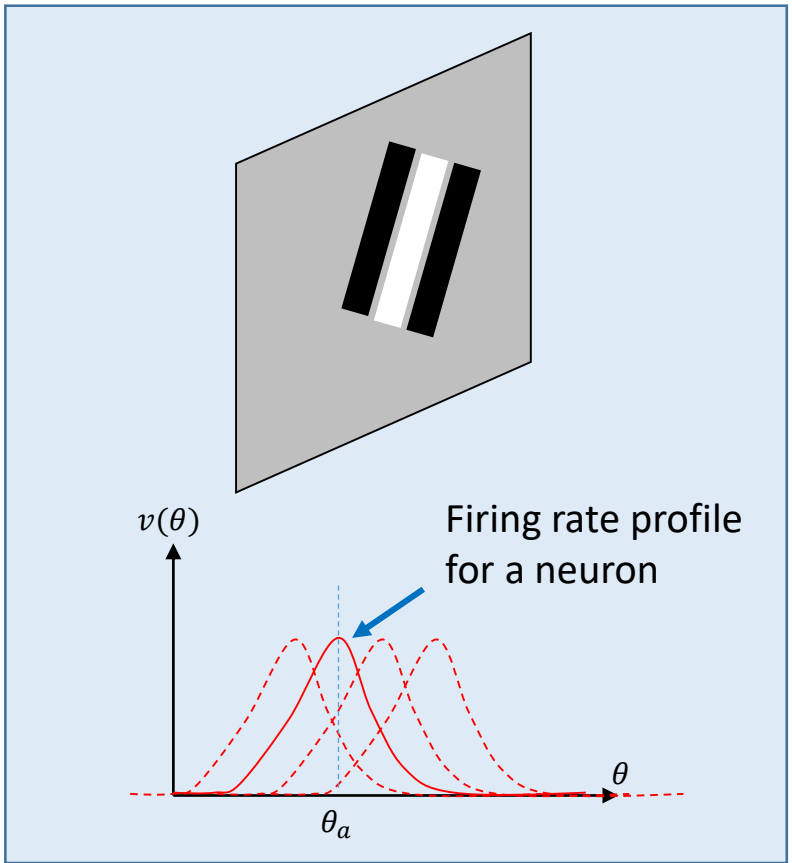
Receptive Fields – Visual Cortex V1



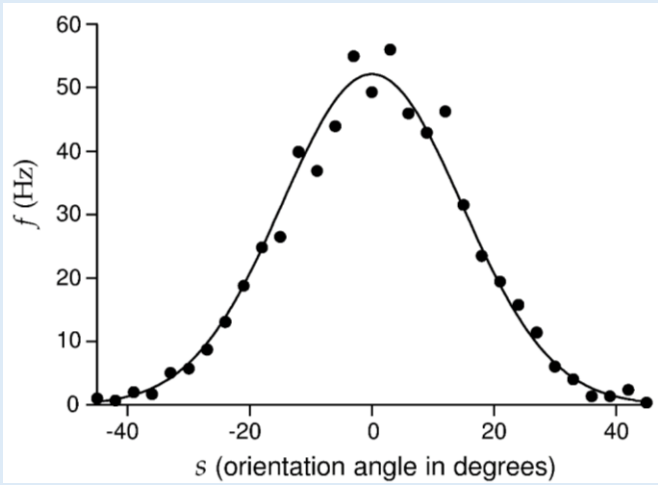
Receptive Fields – Visual Cortex V1

Visual cortex





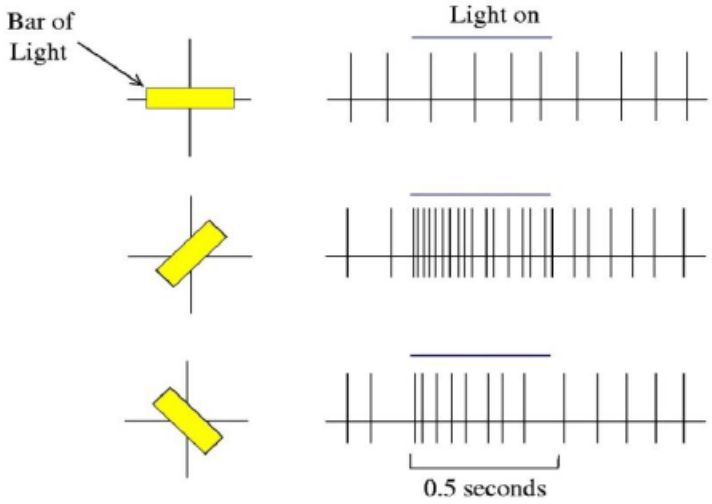
Tuning Curve

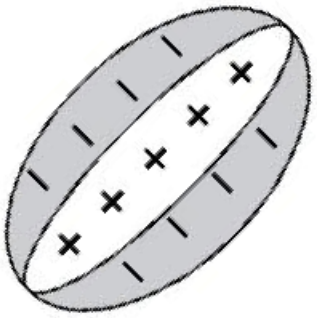


Spike rate vs orientation angle (primary visual cortex of monkey)

Receptive Fields – Visual Cortex V1

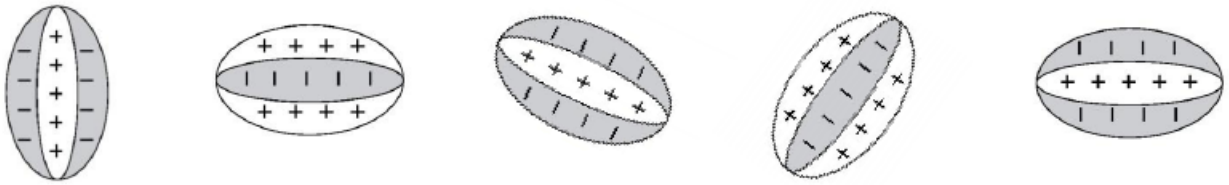
Orientation Preference



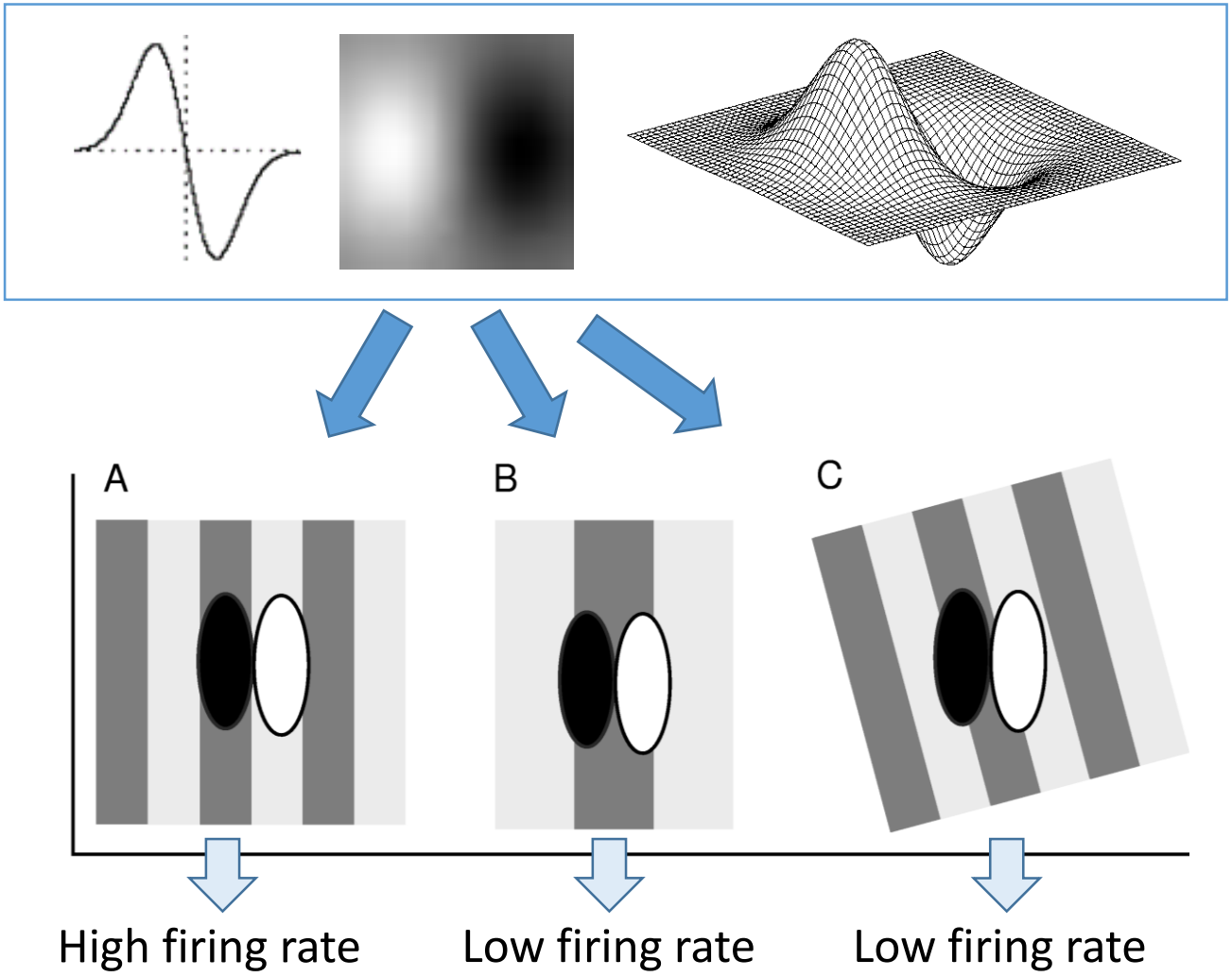


Oriented receptive field of a neuron in primary visual cortex (V1)

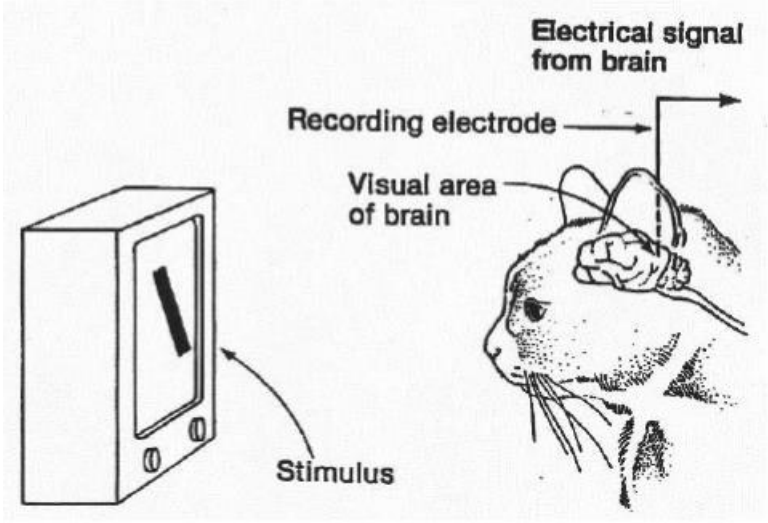
Other examples of oriented receptive fields



Receptive Fields – Visual Cortex V1



Receptive Fields – Visual Cortex V1

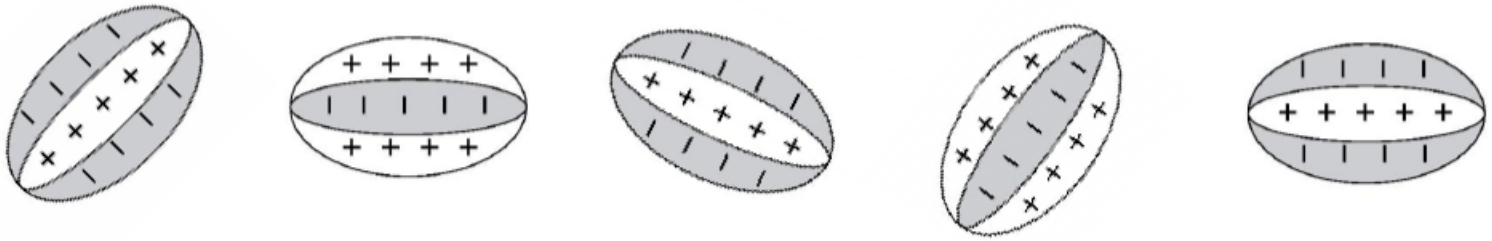


(Hubel and Wiesel, c. 1965)

https://www.youtube.com/watch?v=gedDD6qWDNg

Interpretive Models of Receptive Fields – V1

- The Question: *Why* are receptive fields in V1 shaped in this way?



What are the computational advantages of such receptive fields?

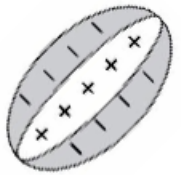
Let's look at one particular ***interpretive*** model of receptive fields

Interpretive Models of Receptive Fields – V1

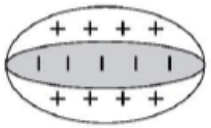
- Efficient Coding Hypothesis: Suppose the goal is to *represent images as faithfully and efficiently as possible* using neurons with receptive fields $\mathbf{RF}_1$, $\mathbf{RF}_2$, etc.
- Given image $\mathbf{I}$, we can reconstruct $\mathbf{I}$ using neural responses $r_1, r_2 \ldots$:

$$\hat{\mathbf{I}} = \sum_i \mathbf{RF}_i r_i$$

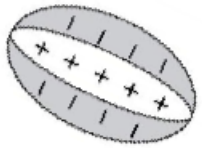
- *Idea*: What are the $\mathbf{RF}_i$ that *minimize* the total squared pixelwise errors between $\mathbf{I}$ and $\hat{\mathbf{I}}$ and are as *independent* as possible?



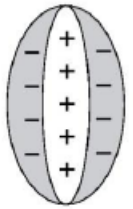
$\mathbf{RF}_1$



$\mathbf{RF}_2$



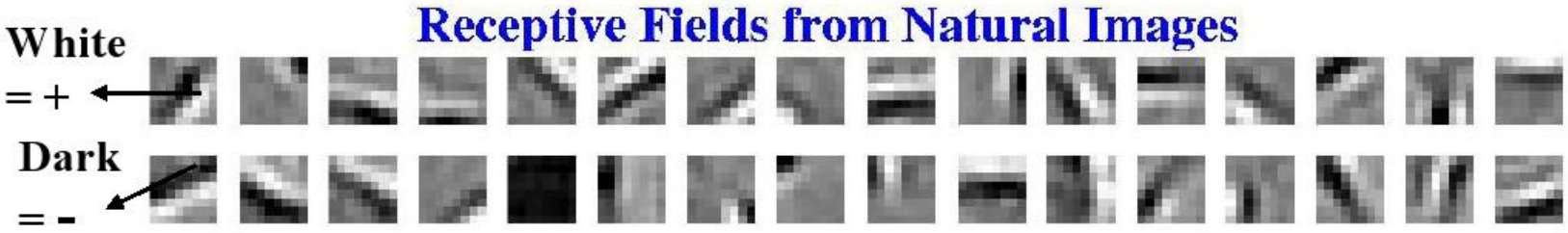
$\mathbf{RF}_3$

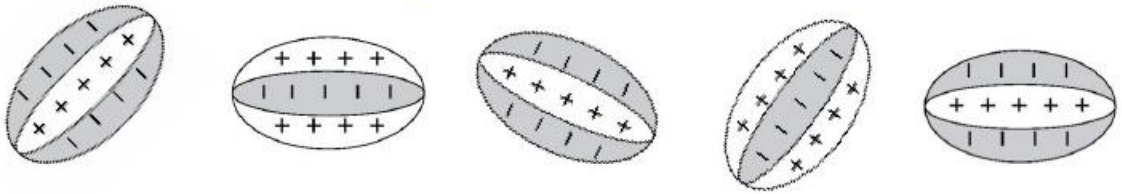


$\mathbf{RF}_4$

We also want **efficiency**, i.e. not all the neurons fire at the same time all the time

Interpretive Models of Receptive Fields – V1



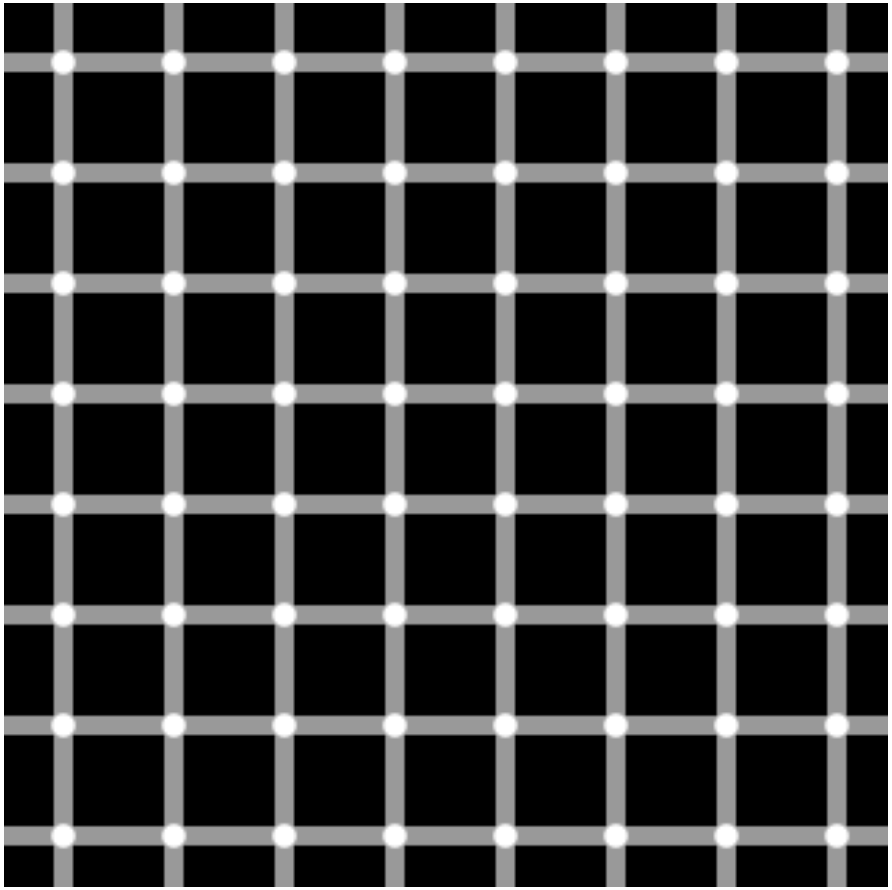


Conclusion: The brain may be trying to find *faithful and efficient* representations of an animal's natural environment

We will develop a model based on these criteria and find that its optimal solutions are the set of oriented gradients

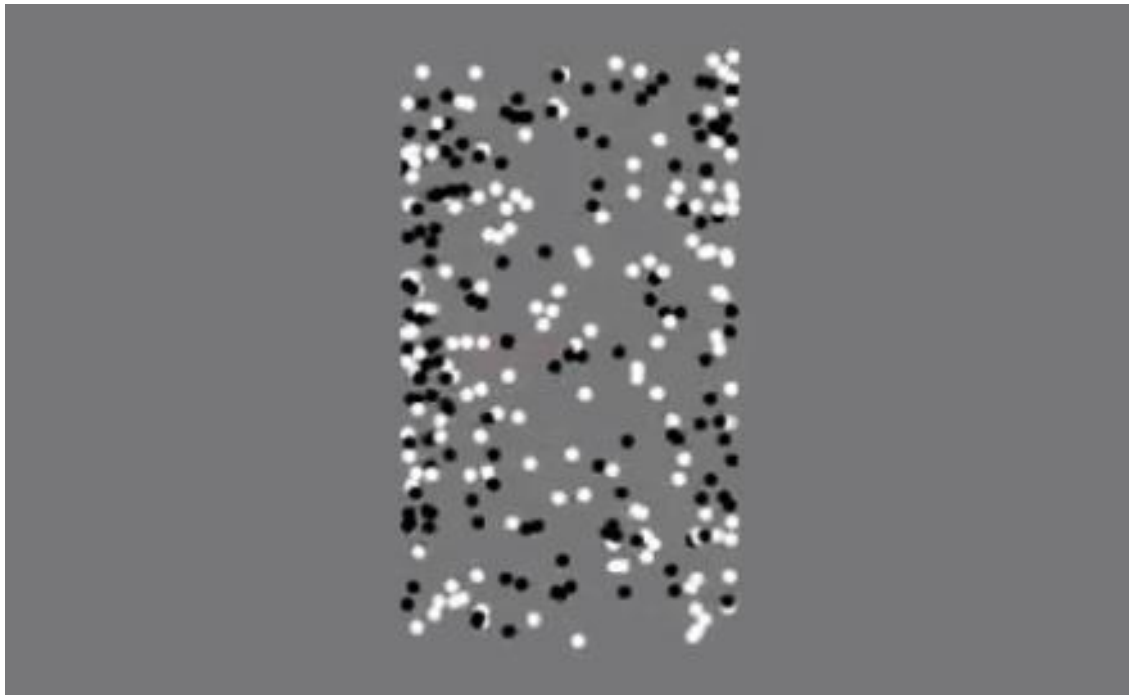
Vision & Perception

Visual Perception – Grid Illusion



- Neurons in visual cortex (and in retina) can inhibit each other and cause illusions that appear as inverse activity

Visual Perception – Rotating Dots Illusion



https://www.youtube.com/watch?v=uqQLUdqXcnE

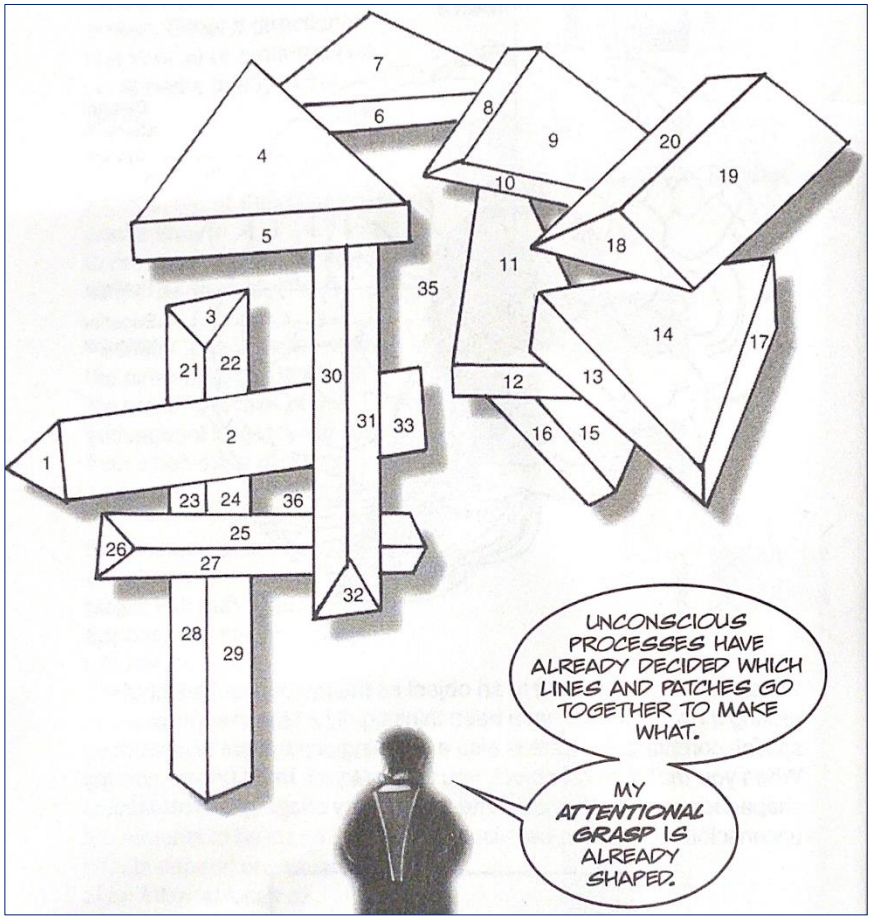
Visual Perception – Seeing in 3D

Example:

- Here, we do not see a set of touching lines and gray patches, but see *individual 3D shapes*

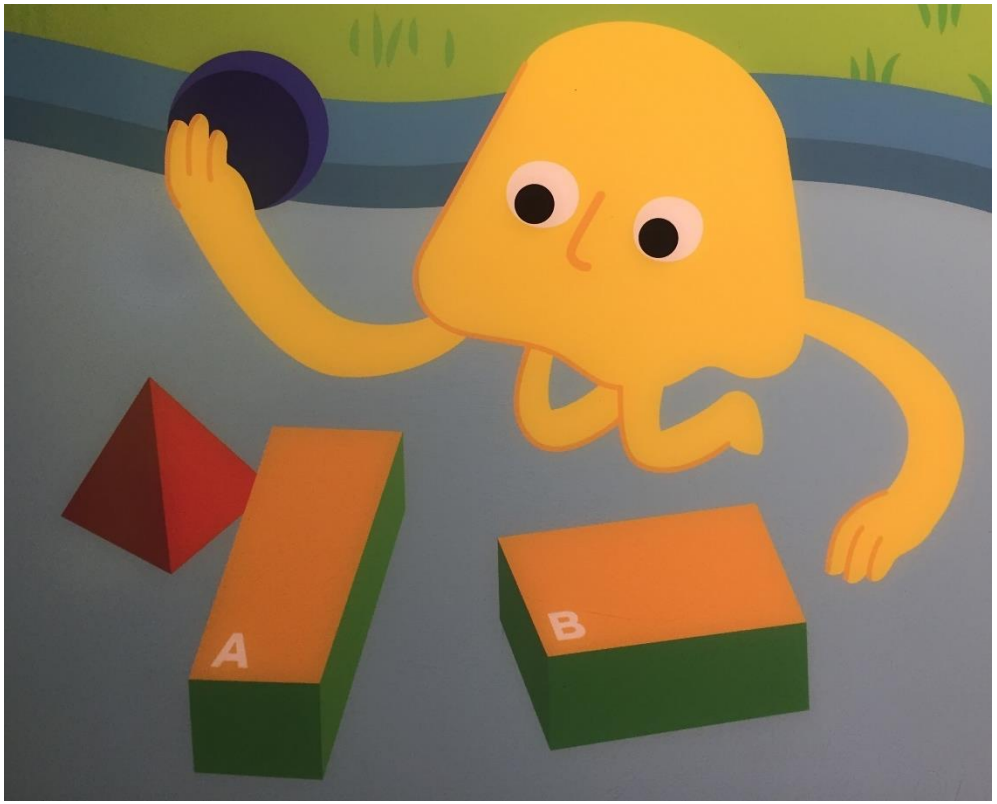
- **In visual attention:**
  - We "see" an object which unconscious processes have "prepared" for us to see

➢ Let's see how this 3D perception can be used to create an illusion



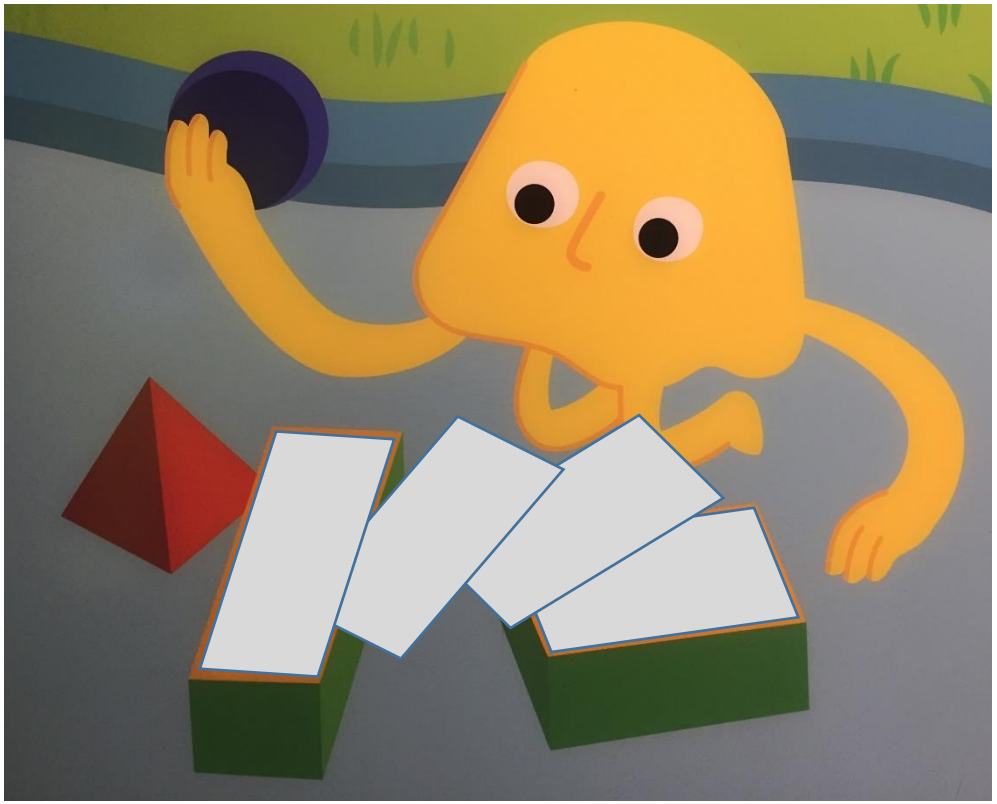
Mind and Brain, *A Graphic Guide*, A. Gellatly & O. Zarate

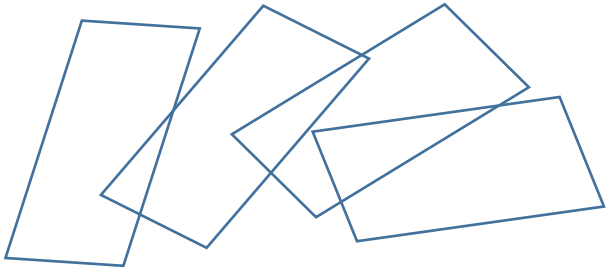
Visual Perception – Seeing in 3D



Perception Exhibit, Science Museum, Boston

Visual Perception – Seeing in 3D





Perception Exhibit, Science Museum, Boston

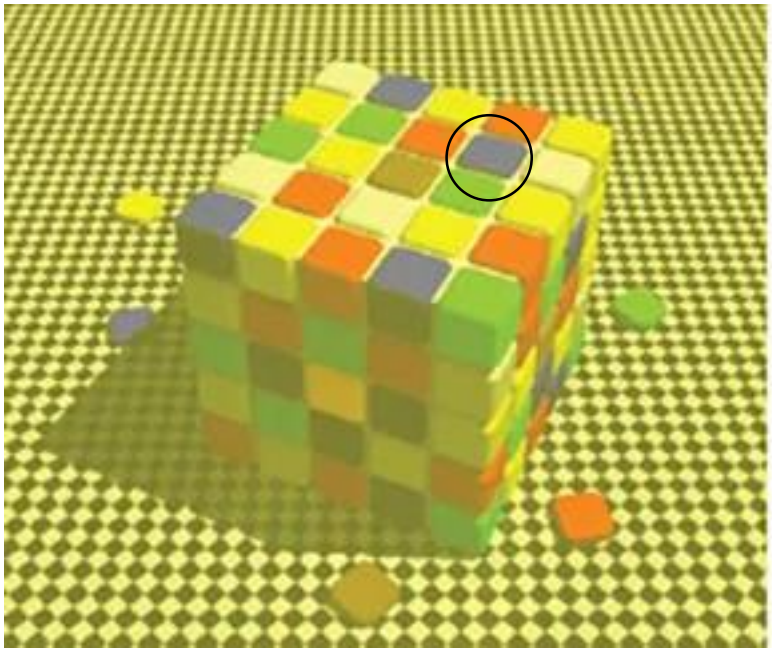
Visual Perception – Color Contrast

- **Local contrast may make us perceive colors differently**

Perception Exhibit, Science Museum, Boston

Visual Perception – Color Context

- **Equal colors may look different because of context**



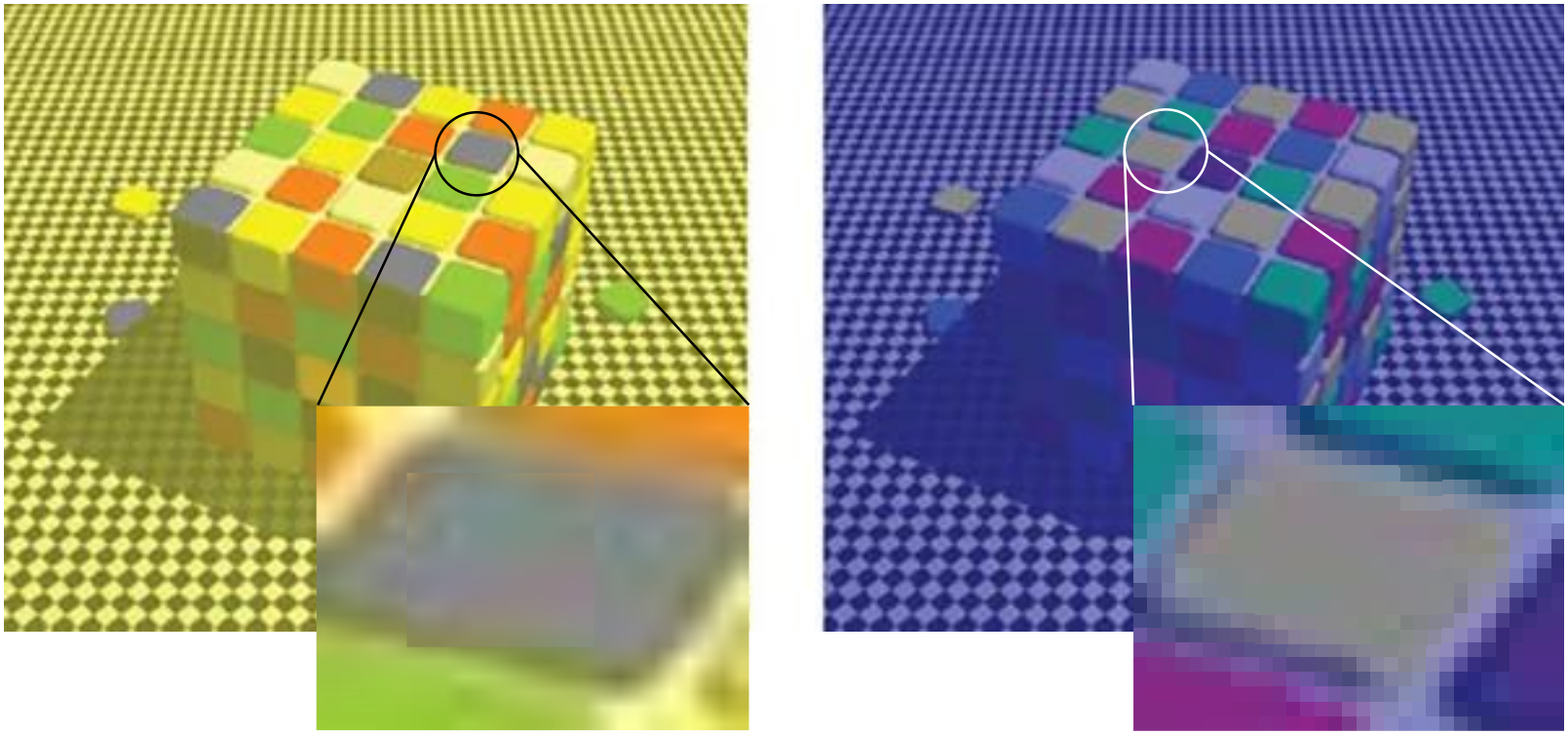
- Blue chips on the top of left cube and the yellow chips on the top of the right cube are identical and are plain gray

➢Let's check this!

Dale Purves & R. Beau Lotto, 2003

Visual Perception – Color Context

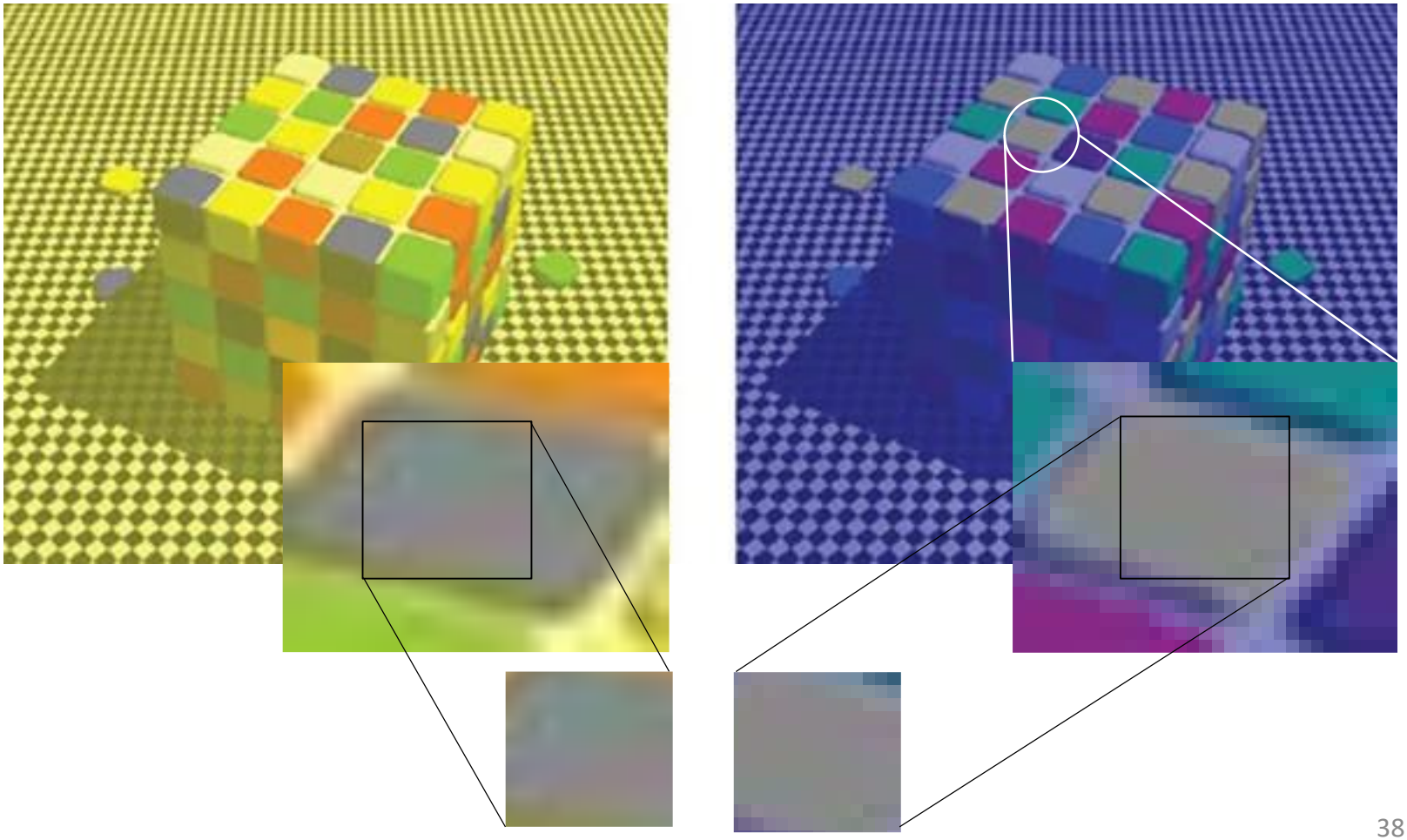
- **Equal colors may look different because of context**



Dale Purves & R. Beau Lotto, 2003

Visual Perception – Color Context

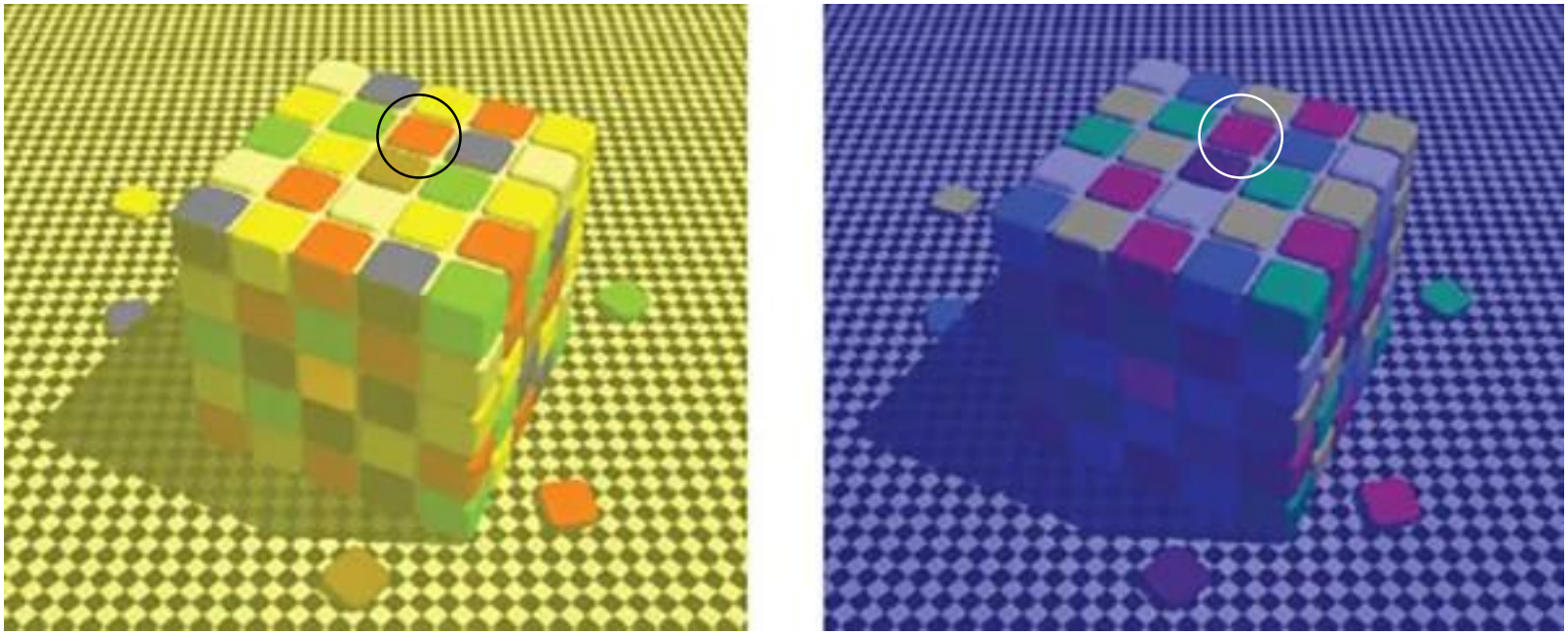
- **Equal colors may look different because of context**



Dale Purves & R. Beau Lotto, 2003

Visual Perception – Color Context

- **Different colors may look similar because of context**



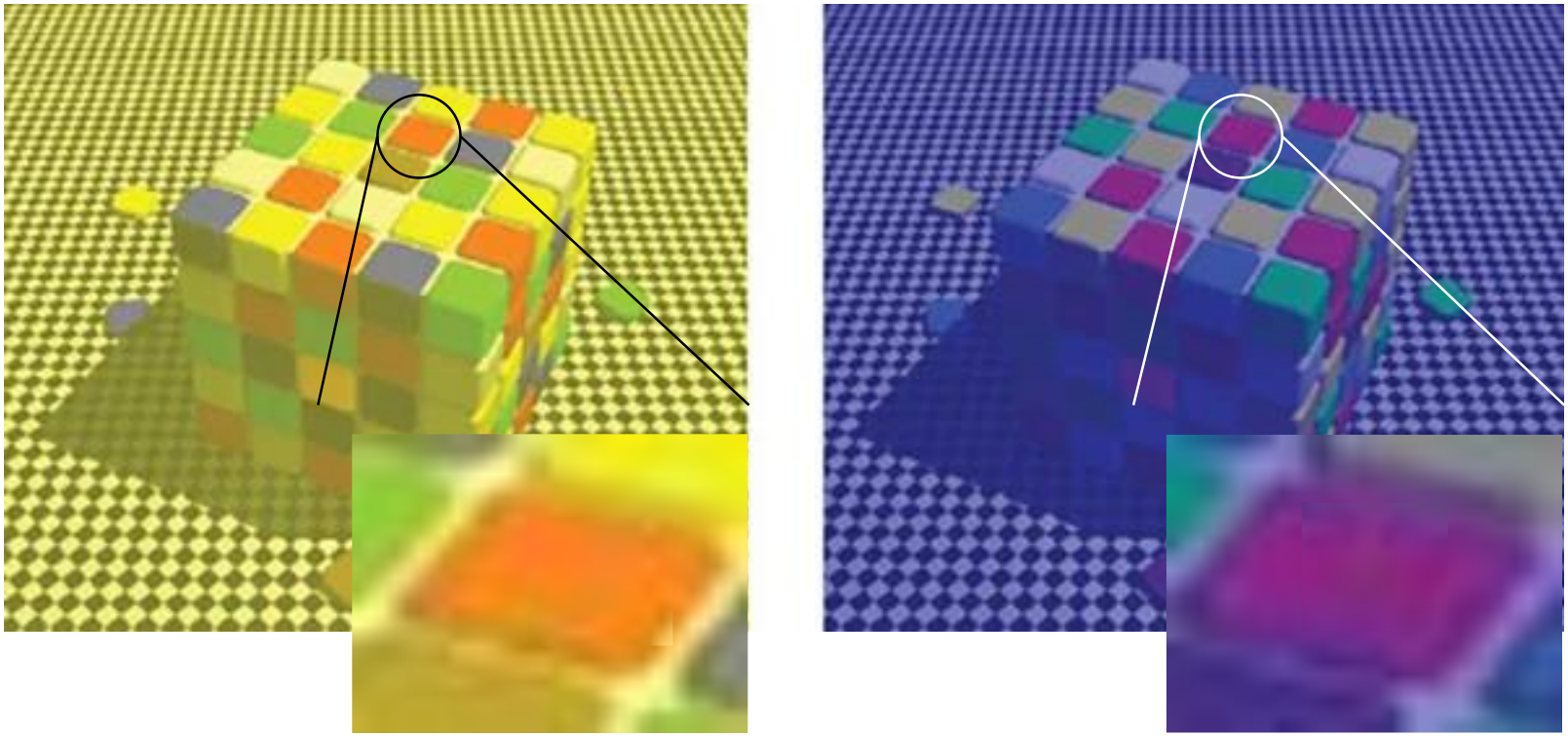
- Red chips on the left and right cubes are not identical colors

➢Let's check this!

Dale Purves & R. Beau Lotto, 2003

Visual Perception – Color Context

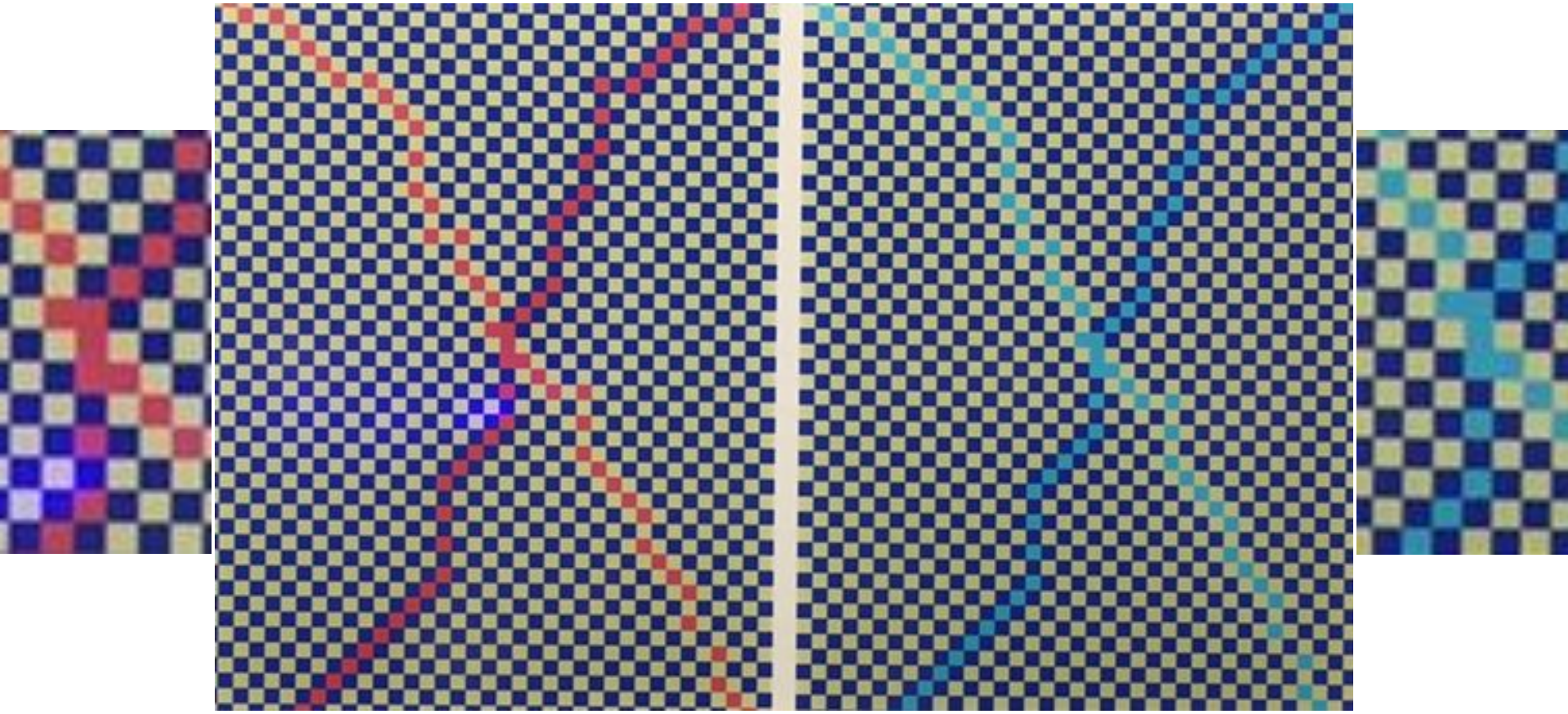
- **Different colors may look similar because of context**



Dale Purves & R. Beau Lotto, 2003

Visual Perception – Local Contrast

- **Local contrasts *tunes* the perception of the same color**



Perception Exhibit, Science Museum, Boston

Visual Perception – The Dress Illusion

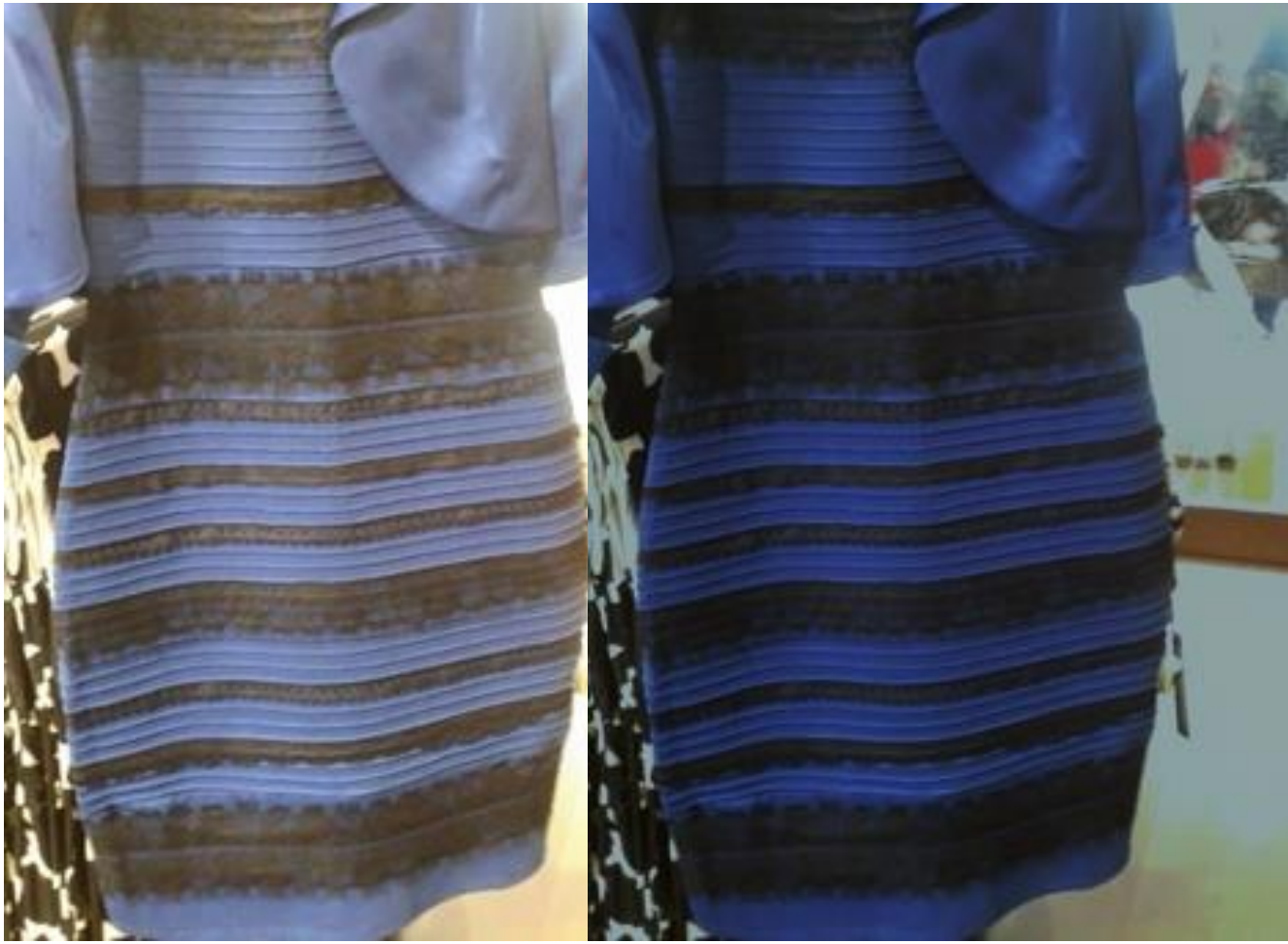
- **What colors are here in this dress?**

Visual Perception – The Dress Illusion

- **Were the colors more similar to which dress here?**

Visual Perception – The Dress Illusion

- **Were the colors more similar to which dress here?**



Visual Perception – The Dress Illusion

- **Were the colors more similar to which dress here?**



Visual Perception – The Dress Illusion

- **What colors are here in this dress?**

Lafer-Sousa et al., 2015

Visual Perception – The Dress Illusion

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Lafer-Sousa et al., 2015

Visual Perception – The Dress Illusion

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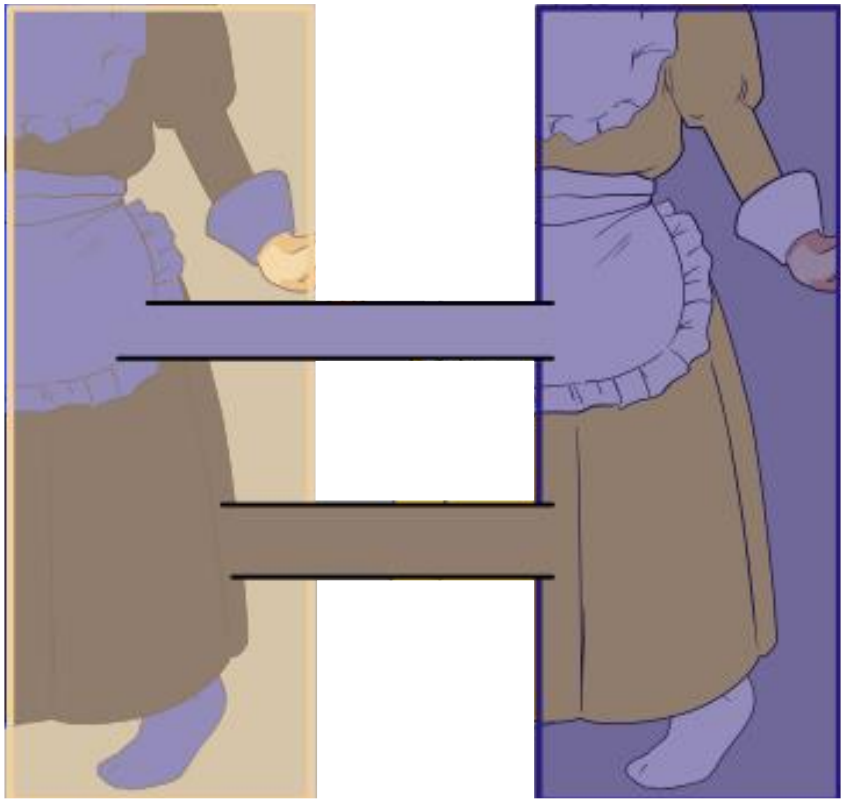
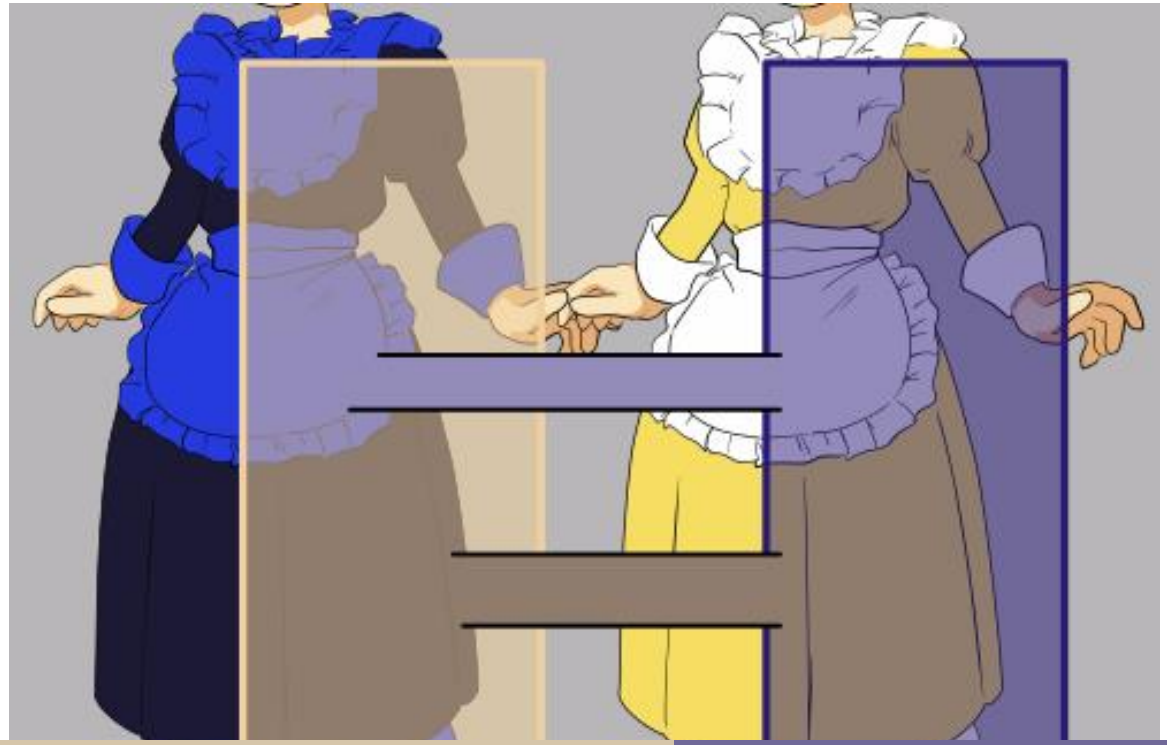


Lafer-Sousa et al., 2015

Visual Perception – The Dress Illusion

- **Your brain tries to discount the chromatic bias of the background daylight to which you are used to**



Those who assume yellow light source, discount yellow and perceive the dress as black and blue

Those who assume blue light source, discount blue and perceive the dress as white and gold

Lafer-Sousa et al., 2015

Visual Perception – The Dress Illusion

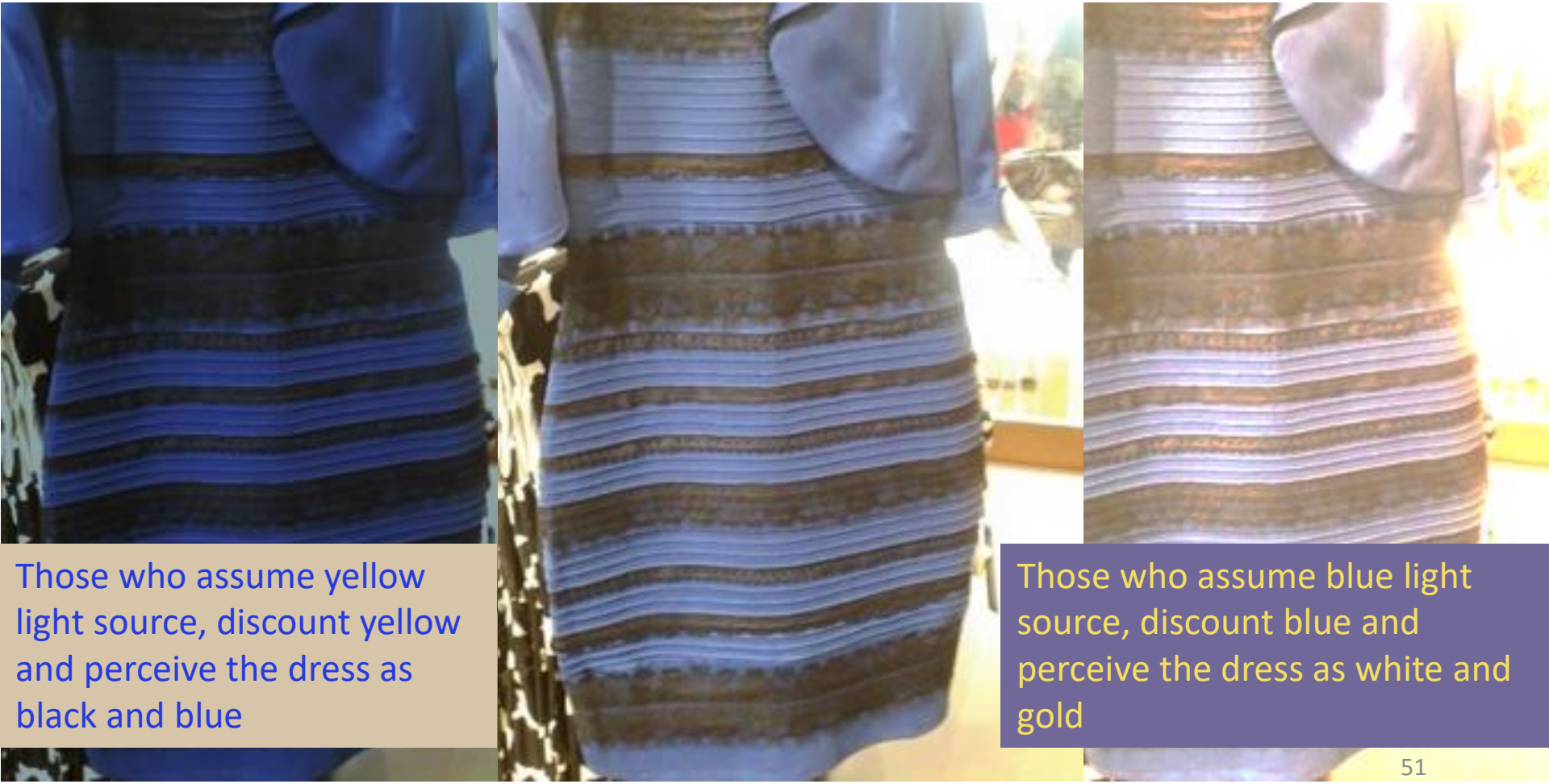
- **Were the colors more similar to which dress here?**

Those who assume yellow light source, discount yellow and perceive the dress as black and blue

Those who assume blue light source, discount blue and perceive the dress as white and gold

Visual Perception – The Dress Illusion

- **Were the colors more similar to which dress here?**



Those who assume yellow light source, discount yellow and perceive the dress as black and blue

Those who assume blue light source, discount blue and perceive the dress as white and gold

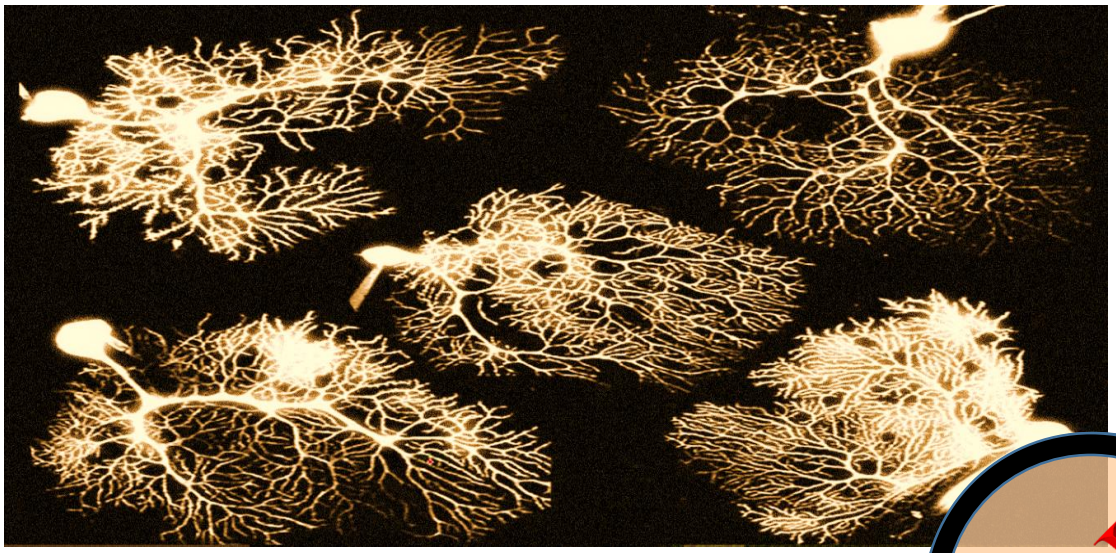
Outline

- Sensing & perception
  - Neurons in the brain
  - Visual cortex & receptive fields
  - Vision & perception
- Neurons & spikes
  - Electrical personality of a neuron
  - Ionic channels
  - Action potential
- The Hudgkin-Huxley equation
  - The passive membrane
  - Voltage-gated channels
  - Anatomy of a spike
- Neuronal dynamics
  - Phase portrait models
  - Fixed points and their stability
  - Bifurcation (saddle-node / Hopf)
  - Simplified 2D models

Next

Neuroscience of Learning, Memory, Cognition

Part I: Neuronal Networks



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Neuron Models