Inside the BRAIN: Neurons and Neural Networks
Fun facts about the brain

The average number of neurons in the brain = 100 billion.

A newborn baby’s brain is as soft and gooey as tapioca pudding!

The adult brain weighs about 3 pounds.

The average number of glial cells in the brain = 10-50 times the number of neurons.
Neural Networks

- Different levels of reference
  - Model specific circuits with known functions
    - Gastro-intestinal circuit of a lobster -- 40 cells
  - Model specific behavioral functions
    - Adding numbers, speaking a language, making pasta...
Decarte

Mind -- Body

What does the Brain have to do with it?

Materialism
Why is the brain made of GOO?

Best Computer technology at present has efficiency 0.0000007 JOULES work for 10 MILLION OPERATIONS in 1 SEC!

The brain cost us almost nothing to run...

The BRAIN 0.000000000000000016 JOULES of work for 10 MILLION OPERATIONS in 1 SEC!

The brain is ~100 MILLION times more efficient than the best computer technology.
Evolution and the Brain

From the inside out... from the simplest most primitive responses

The Triune Brain - (P. MacLean 1990)
Most bilaterally symmetrical animals exhibit

- cephalization, the concentration of the nervous system in the head end

- centralization, the presence of a central nervous system
**Dataset:** All measurements of hominin cranial capacity available in the literature as of September 2000, for skulls older than 10,000 years old. Adult specimens only. Average is presented where multiple measurements were made. N = 215 points.

**Data source:** C. De Miguel and M. Henneberg (2001). "Variation in hominid brain size: How much is due to method?" *Homo* 52(1), pp. 3-58. Data copied into Excel from Appendix: "From Lucy to Boskop" (pp. 20-49).

**TWEAK** Increase brain size. Enlarging size by adding more neurons increases processing capacity.

**TRADE-OFFS** Neurons consume a lot of energy. And as brains get bigger, the axons, or “wires,” that connect neurons have to become longer, which makes them slower.

**TWEAK** Increase interconnectedness. Adding more links between distant neurons enables brain parts to communicate faster.

**TRADE-OFFS** The added wiring eats up energy (and takes up space).

**TWEAK** Increase signaling speed. Could be achieved by making axons thicker.

**TRADE-OFFS** Thicker axons consume more energy (and take up more space) than thinner ones do.

**TWEAK** Pack more neurons into the existing space. Achievable by shrinking neurons or axons, or both.

**TRADE-OFFS** If axons or neurons get too small, they tend to fire randomly.

**BOTTOM LINE**

- Slows processing
- Costs too much energy
- Signaling gets too noisy
Nervous System Structure

Central Nervous System (CNS)
- Brain and spinal cord
- Integrative and control centers

Peripheral Nervous System (PNS)
- Cranial nerves and spinal nerves
- Communication lines between the CNS and the rest of the body

Sensory (afferent) division
- Somatic and visceral sensory nerve fibers
- Conducts impulses from receptors to the CNS

Motor (efferent) division
- Motor nerve fibers
- Conducts impulses from the CNS to effectors (muscles and glands)

Sympathetic division
- Mobilizes body systems during activity ("fight or flight")

Parasympathetic division
- Conserves energy
- Promotes "housekeeping" functions during rest

Autonomic nervous system (ANS)
- Visceral motor (involuntary)
- Conducts impulses from the CNS to cardiac muscles, smooth muscles, and glands

Somatic nervous system
- Somatic motor (voluntary)
- Conducts impulses from the CNS to skeletal muscles
Figure 3.19  Gross appearance of the brain stem with the cerebral hemisphere dissected away. Note the organization of brain stem structures in relation to the cerebral hemisphere. Lateral view.
Levels of Investigation

1 m  CNS
10 cm Systems
1 cm  Maps
1 mm  Networks
100 µm Neurons
1 µm  Synapses
1 Å   Molecules
Grey Matter
(cell bodies)

White Matter
(axons - myelin)
Neurons are Beautiful! (Bartlett's Pictures)
Figure 2.17  Examples of neurons illustrating the variety of shapes in different areas of the brain. (With permission from Kuffler, Nicholls and Martin [1984]. From Neuron to Brain. Sunderland MA: Sinauer Associates.)
Dendrites

Presynaptic terminals

Cell body (soma)

Axon hillock

Myelinated axon

Graded EPSP (analog computer)

Trigger: all-or-none spike initiated (digital computer)

Conducted all-or-none spike (conduction of spike to next cell)
THE ANATOMY of
A MODEL NEURON

Firing RATE to other Cells
Pre synaptic EPSPs

Transform to internal
“arousal” to RATE or
Frequency of Spikes;
Probably Nonlinear including
threshold

activation
approximation

Decision
Capacity

Memory of
Network

\[ a_i = \sum w_{ij} x_i \]

\[ f(a_i, \theta) \]

Represents what the
Dendrites compute from
EPSPs and IPSPs

Synaptic weights are
represented by real valued
numbers and can be
changed by a learning rule

\[ x_1, x_2, x_3 \]
(sensory input)
THE WORLD
Neural Networks

Figure 1. Models assume two sets of \( N \) neurons alpha projecting to beta. (Every neuron in alpha projects to every neuron in beta. This drawing has \( N = 6 \). From “Distinctive Features, Categorical Perception, and Probability Learning: Some Applications of a Neural Model” by J. A. Anderson, J. W. Silverstein, S. A. Ritz, and R. S. Jones, 1977, Psychological Review, 84, p. 416. Copyright 1977 by the American Psychological Association, Inc. Reprinted by permission.)
electrical activity of neurons

- the brain has electrical activity
- EEG ERP
- Source Currents?
- Brain states?
MUSIC in the Brain
Spiking Codes for Specific Stimuli
Types of brain waves

Examples are given in Figure 4.5 of the various common type of brain waves that can be recorded from humans. Types of brain waves are listed also in Table 4.1.

Table 4.1 Types of brain waves in the human electroencephalogram, their frequencies, and conditions when present

<table>
<thead>
<tr>
<th>Type of wave or rhythm</th>
<th>Frequency per second (range)</th>
<th>Condition when present</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>8–12</td>
<td>Awake, relaxed, eyes closed</td>
</tr>
<tr>
<td>Beta</td>
<td>16–30</td>
<td>Awake, no movement</td>
</tr>
<tr>
<td>Gamma</td>
<td>30–50</td>
<td>Awake</td>
</tr>
<tr>
<td>Delta</td>
<td>0.5–4</td>
<td>Asleep</td>
</tr>
<tr>
<td>Theta</td>
<td>5–7</td>
<td>Awake, affective or stress</td>
</tr>
<tr>
<td>Kappa</td>
<td>8–12</td>
<td>Awake, problem solving (?)</td>
</tr>
</tbody>
</table>

Correlation of two brains doing the same thing!
Brain Music: Schizophrenia
Neural Transmission

The synapse typically has two parts:

A presynaptic structure containing packets of signaling chemicals, or neurotransmitters, and a postsynaptic structure on the dendrites of the receiving neuron that has receptors for the neurotransmitter molecules.
D.O. Hebb

Neurons that FIRE together WIRE together!

If two neurons respond together the synapse between them will increase in efficacy.
Neural Comm.
Neurons and Neural Networks

Starting simple: receptors, pathways, and circuits

1) Neurons work using an integrate-and-fire action
2) Connections are either excitatory or inhibitory
3) Idealized neurons are used in artificial neural nets to model brain function
4) Neurons typically form two-way pathways, providing the basis for re-entrant connectivity
5) The nervous system is formed into arrays or maps of neurons
6) Hebbian cell assemblies underlie the change from transient to stable, lasting connections
Receptive Fields can be complex

Figure 2.27 Two types of circular center–surround receptive fields in the retina. When the light is shone on the center of the receptive field, the on-center cell responds vigorously, while the center cell is silent. When the light is shone in the annular surround, the opposite effect is achieved. Under diffuse illumination of both the center and the surround, both cells respond weakly. (With permission from Coren Ward [1989]. *Sensation and Perception*, 3rd ed. Copyright © 1989 Harcourt Brace Jovanovich, Inc.)
3.0 Arrays and Maps

Neuronal arrays usually have two-way connections

Arrays and Maps

Maps flow into other maps: The nervous system often uses layers of neurons in giant arrays.
elaborate structures are required for these purposes or relations to surface. We will therefore make it common practice that once a substrate complication is well understood, it will be removed to facilitate the structural (and possibly the cognitive) end of the description.

Figure 1.1: A schematic representation of the brain as a system of sequential stations – input (S), associative central processing (A) and motor output (M). (From ref. [15], by permission.)
NEURAL NETWORKS: NETTALK AGAIN

The diagram shows a neural network with layers of units. The input units are labeled 'THE', 'Y', and 'COULD'. The hidden units are connected to these, and the output units are labeled 'k'. The diagram illustrates the structure and connections of the network.
**CENTRAL NERVOUS SYSTEM (CNS)**
- Brain
- Spinal cord

**PERIPHERAL NERVOUS SYSTEM (PNS)**
- Cranial nerve
- Ganglia outside CNS
- Spinal nerves
- Autonomic nerves to vicera and somatic outside vicera
The brain and spinal cord contain fluid-filled spaces

Figure 28.11B
Arrays and Maps

Sensory and motor systems work together
Overall Nervous System and Brain Structure

- The brain is organized in 10,000s of neurons to 10s of Millions
- Hierarchy especially in Motor and Sensory systems
- Parallel and balancing systems
The vertebrate brain develops from three anterior bulges of the neural tube

- The vertebrate brain evolved by the enlargement and subdivision of three anterior bulges of the neural tube
  - Forebrain
  - Midbrain
  - Hindbrain

- Cerebrum size and complexity in birds and mammals correlates with sophisticated behavior
The autonomic nervous system consists of two sets of neurons that function antagonistically on most body organs.

- The parasympathetic division primes the body for activities that gain and conserve energy.
- The sympathetic division prepares the body for intense, energy-consuming activities.

Opposing actions of sympathetic and parasympathetic neurons regulate the internal environment.
PARASYMPATHETIC DIVISION

Brain Constricts pupil
Stimulates saliva production
Constricts bronchi
Slows heart

Spinal cord

Eye
Salivary glands
Lung
Heart
Liver
Stomach
Adrenal gland
Pancreas
Intestines
Bladder
Genitals

Promotes erection of genitals

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SYMPATHETIC DIVISION

Dilates pupil
Inhibits saliva production
Relaxes bronchi
Accelerates heart
Stimulates epinephrine and norepinephrine release
Stimulates glucose release
Inhibits stomach, pancreas, and intestines
Inhibits urination
Promotes ejaculation and vaginal contractions
<table>
<thead>
<tr>
<th>Embryonic Brain Regions</th>
<th>Brain Structures Present in Adult</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forebrain</td>
<td>Cerebrum (cerebral hemispheres; includes cerebral cortex, white matter, basal ganglia)</td>
</tr>
<tr>
<td></td>
<td>Diencephalon (thalamus, hypothalamus, posterior pituitary, pineal gland)</td>
</tr>
<tr>
<td>Midbrain</td>
<td>Midbrain (part of brainstem)</td>
</tr>
<tr>
<td>Hindbrain</td>
<td>Pons (part of brainstem), cerebellum</td>
</tr>
<tr>
<td></td>
<td>Medulla oblongata (part of brainstem)</td>
</tr>
</tbody>
</table>

Embryonic Brain Regions:
- Forebrain
- Midbrain
- Hindbrain

Brain Structures Present in Adult:
- Cerebrum (cerebral hemispheres; includes cerebral cortex, white matter, basal ganglia)
- Diencephalon (thalamus, hypothalamus, posterior pituitary, pineal gland)
- Midbrain (part of brainstem)
- Pons (part of brainstem), cerebellum
- Medulla oblongata (part of brainstem)

Embryo one month old
- Forebrain
- Midbrain
- Hindbrain

Fetus three months old
- Cerebral hemisphere
- Diencephalon
- Midbrain
- Pons
- Cerebellum
- Medulla oblongata
- Spinal cord
The structure of a living supercomputer: The human brain

<table>
<thead>
<tr>
<th>Brain Structure</th>
<th>Major Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brainstem</td>
<td>Conducts data to and from other brain centers; homeostatic control; coordinates body movement</td>
</tr>
<tr>
<td>Medulla oblongata</td>
<td>Controls breathing, circulation, swallowing, digestion</td>
</tr>
<tr>
<td>Pons</td>
<td>Controls breathing</td>
</tr>
<tr>
<td>Midbrain</td>
<td>Receives and integrates auditory data; major visual center in nonmammalian vertebrates; coordinates visual reflexes in mammals; sends sensory data to higher brain centers</td>
</tr>
<tr>
<td>Cerebellum</td>
<td>Coordinates body movement; learns and remembers motor responses</td>
</tr>
<tr>
<td>Thalamus</td>
<td>Input center for sensory data going to the cerebrum; output center for motor responses leaving the cerebrum; data sorting</td>
</tr>
<tr>
<td>Hypothalamus</td>
<td>Homeostatic control center; controls pituitary gland; biological clock</td>
</tr>
<tr>
<td>Cerebrum</td>
<td>Sophisticated integration; memory, learning, speech; emotions; formulates complex behavioral responses</td>
</tr>
</tbody>
</table>
Figure 28.16

FRONTAL LOBE

PARIETAL LOBE

TEMPORAL LOBE

OCCIPITAL LOBE

Frontal association area

Motor cortex

Somatosensory cortex

Speech

Taste

Reading

Smell

Hearing

Auditory association area

Vision

Visual association area

Somatosensory association area

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Figure 28.16
Most of the cerebrum’s integrative power resides in the cerebral cortex of the two cerebral hemispheres.
In lateralization, areas in the two hemispheres become specialized for different functions

<table>
<thead>
<tr>
<th>Left Hemisphere</th>
<th>Right Hemisphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movement of the right side</td>
<td>Movement of the left side of the body</td>
</tr>
<tr>
<td>Sensation on the right side</td>
<td>Sensation on the left side of the body</td>
</tr>
<tr>
<td>Vision in the right half</td>
<td>Vision in the left half</td>
</tr>
<tr>
<td>Speech/Language Left</td>
<td>Music and art appreciation, drawing</td>
</tr>
<tr>
<td>sequential</td>
<td>simultaneous</td>
</tr>
<tr>
<td>analytical</td>
<td>holistic</td>
</tr>
<tr>
<td>verbal</td>
<td>imagistic</td>
</tr>
<tr>
<td>logical</td>
<td>intuitive</td>
</tr>
<tr>
<td>linear algorithmic processing</td>
<td>holistical algorithmic processing</td>
</tr>
<tr>
<td>present and past</td>
<td>present and future</td>
</tr>
</tbody>
</table>
The cerebral cortex is a mosaic of specialized, interactive regions

- The motor cortex sends commands to skeletal muscles
- The somatosensory cortex receives information about pain, pressure, and temperature
- Several regions receive and process sensory information (vision, hearing, taste, smell)
• The association areas are the sites of higher mental activities (thinking)

  – Frontal association area (judgment, planning)

  – Auditory association area

  – Somatosensory association area (reading, speech)

  – Visual association area
The limbic system is involved in emotions, memory, and learning

- The limbic system is a functional group of integrating centers in the cerebral cortex, thalamus, and hypothalamus

- It is involved in emotions, memory (short-term and long-term), and learning
  - The amygdala is central to the formation of emotional memories
  - The hippocampus is involved in the formation of memories and their recall
A basic question in cognitive neuroscience is how nerve cells combine to perform complex cognitive functions such as perception, memory, and action. While neurons form the basic building block of cognition, we are still unfolding how they work both as individual cells and in synchrony in large scale arrays.

Some working assumptions about how neurons work -- such as the integrate-and-fire neuron, two-way pathways, cell assemblies and artificial neural nets -- have allowed scientists to begin to model the complex and dynamic activity in the brain that underlies human cognition.