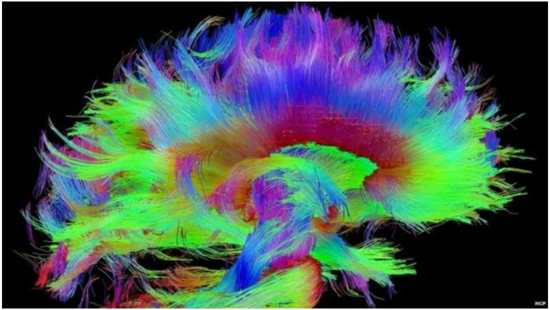
CS 4884: Computing the Brain

Computional Biology and Bioinformatics Capstone Course

T. M. Murali

January 18 and 20, 2022

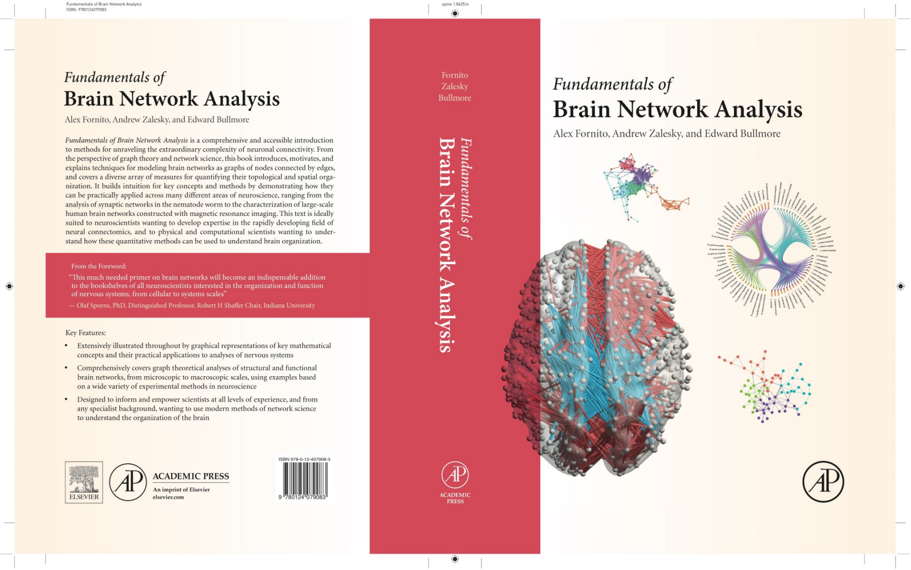


This course is NOT about neural networks or deep learning.

Course Information

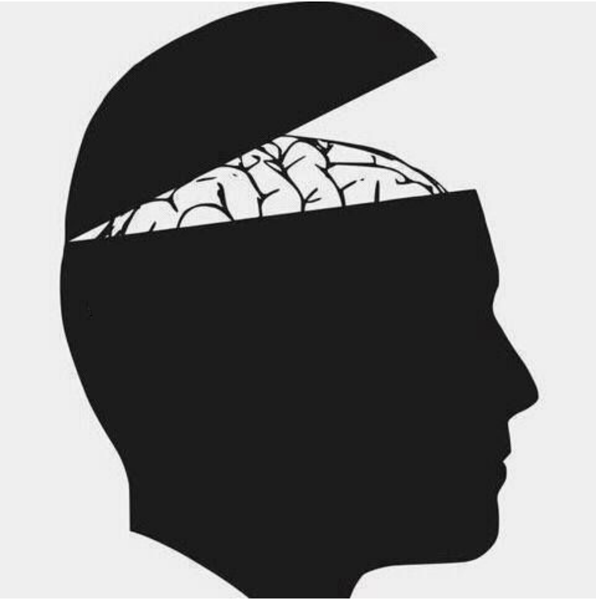
- Meet on Tuesdays and Thursdays, 2pm–3:15pm, MCB 110A.
- Office hours: by appointment and during class times in second half of semester.
- Course website: http://bioinformatics.cs.vt.edu/~murali/teaching/2022-spring-cs4884/. Consult this website regularly. Course schedule is subject to change.

Textbook



Course website contains an online link to the textbook.

Course Pre-requisite



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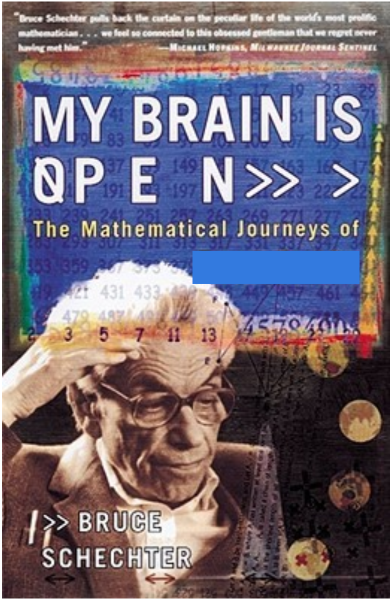

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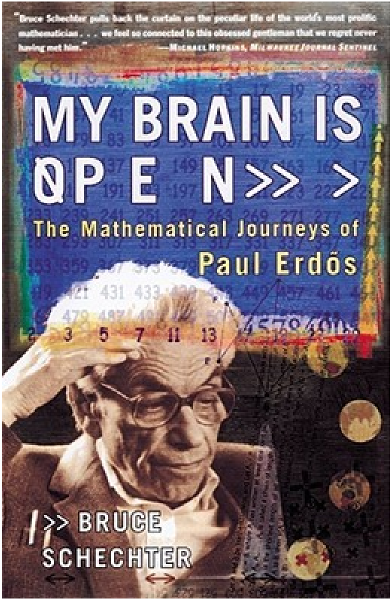

Course Structure

- Lectures based on the textbook

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- Assignments (2–3)

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- Final project

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- Assignments (2–3)
- Final project
- Participation in VTURCS Research Symposium in late April.

Grading

- Assignments: 40%
- Final project: 60%

Assignments

- Typically, I will ask you to write code to replicate analysis in one or two figures in a research paper.
- These assignments may organically come about from class discussions.
- You will have about two weeks to complete assignments.
- What do you turn in?
  - Fully working code, e.g., on GitHub.
  - A short report on the results of your analysis, including the figures, discussion of difficulties you faced, how you solved them, and observations on your results.

Goals of the Course

Learn computational methods that use network/graph theory to understand the brain at three levels:

Anatomical

Cellular

Molecular

to gain insights into brain functions in health and disease.

History of the Brain: Pre-History

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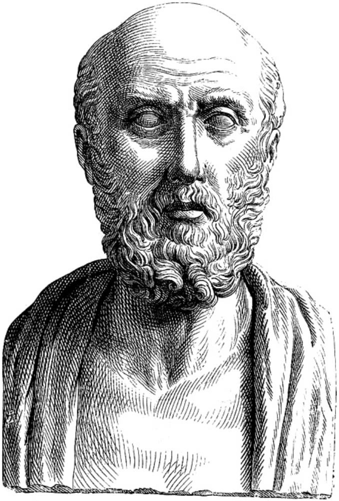
- Egypt (c. 3000 BC): Aware of symptoms of brain damage, but considered the heart to the repository of memories.
- India (c. 400 BC): Charaka described symptoms and treatments of epilepsy.

Ancient Greece

- Study of the brain was not based on dissection.
- Hippocrates (460–379 BC): Brain is the organ of sensation and intelligence.



The birth and evolution of neuroscience through cadaveric dissection, Moon K1, Filis AK, Cohen AR. Neurosurgery. 2010 Sep;67(3):799–809

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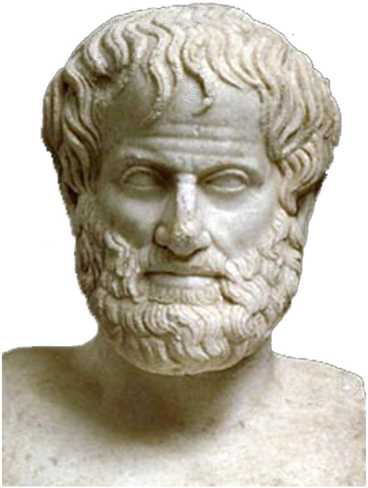

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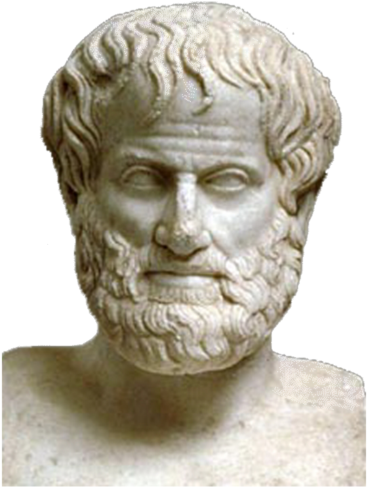

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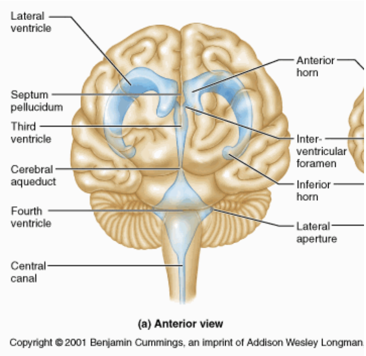
- Herophilus (c. 325–255 BC):
  - Father of neuroanatomy, first dissector in the Western tradition.
  - Discovered ventricles, distinguished between cerebrum and cerebellum.



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Galen (130–200 AD)

- Theories dominated Western and Byzantine medicine till the 16th century.
- Used animal dissections.
- Structure-Function: cerebellum (hard) receives sensations and cerebrum (soft) stores memories.
- The brain is the location of the mind.

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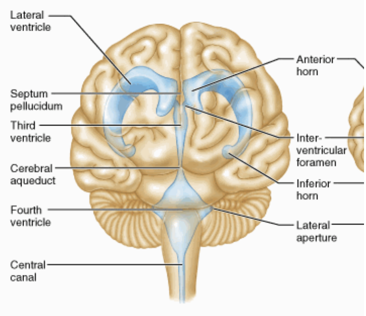
- Brain controls senses and motor functions by movement of fluids to and from ventricles through nerves (which are hollow, cf. arteries).



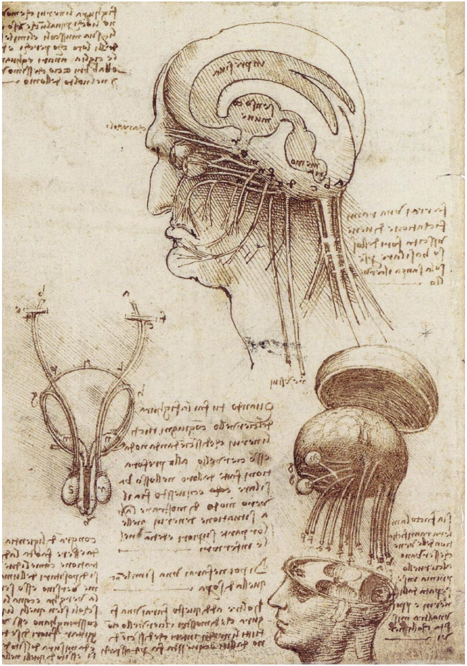
(a) Anterior view

The Next 1300 Years

- Dark Ages in Europe.
- Arabs copied Galen's text among others.
- Islamic surgeon Abu al-Qasim al-Zahrawi (1000 AD) described several treatments for neurological disorders.

Renaissance (14th–16th Centuries)

- Increased recognition of need for dissection to acquire new knowledge about the body's internal organs.
- Printing press (1439 AD) circulated Galen's works.
- Renaissance and Reformation of the Church promoted fresh thinking.
- Dissection resulted in detailed anatomical drawings.

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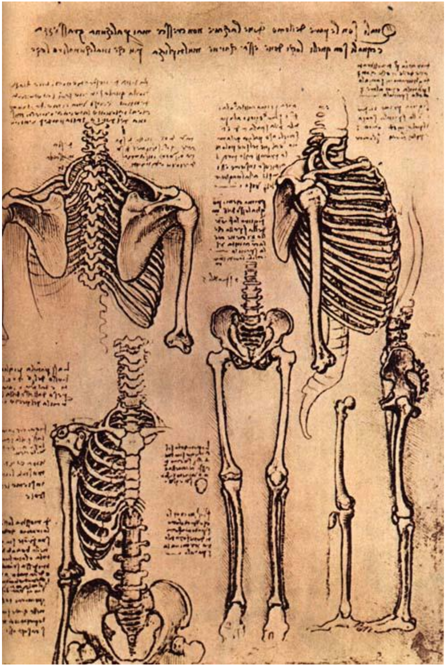
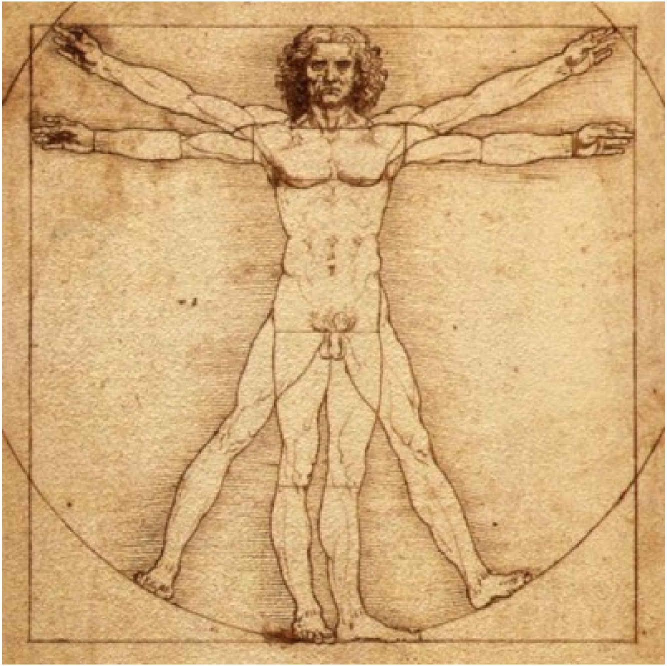
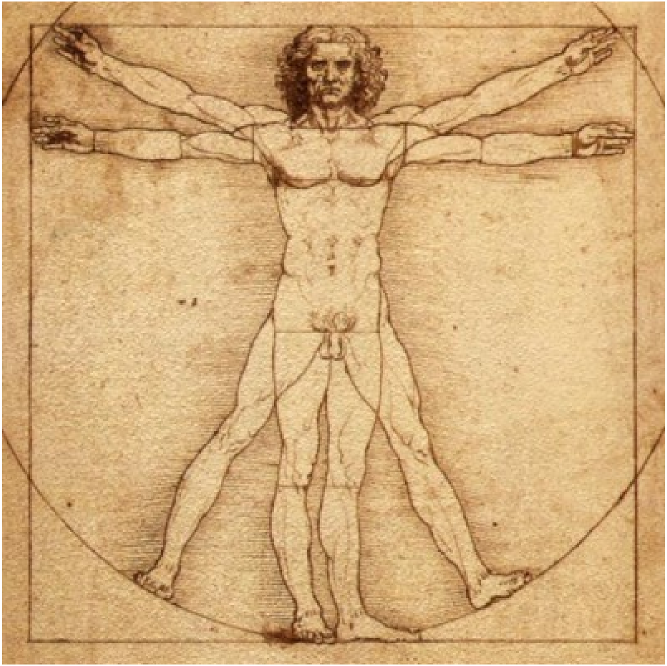


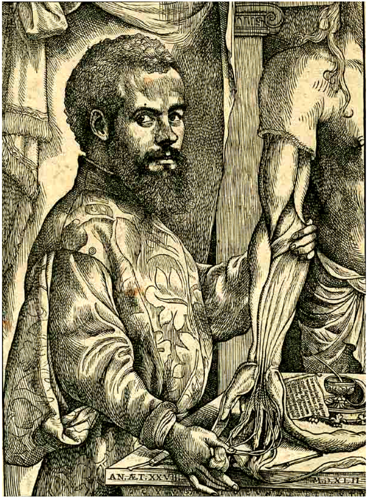




Leonardo da Vinci (1452–1519)

Andreas Vesalius (1514–1564)

- Used skillful dissection of cadavers.



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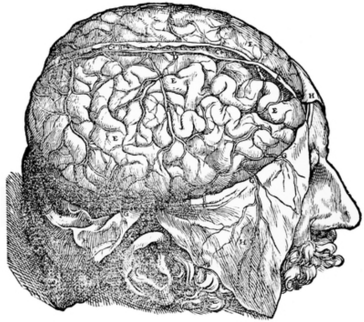

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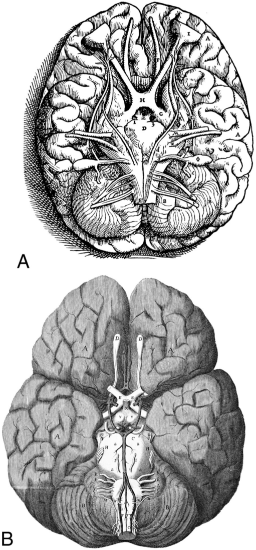

A

B

Contemporaries and Descendants of Vesalius

Mathematics Genealogy Project

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- Mirrors

A service of the NDSU Department of Mathematics, in association with the American Mathematical Society.

Gemma (Jemme Reinerszoon) Frisius

Biography

Magister Philosophiae, Medicinae Doctor Université Catholique de Louvain 1529, 1536

Dissertation:

Advisor: Petrus (Pieter de Corte) Curtius

Students:
Click here to see the students listed in chronological order.

Name	School	Year	Descendants
John Dee	University of Cambridge and Université Catholique de Louvain	1546	1
Gerardus Mercator	Université Catholique de Louvain	1532	2
Johannes Stadius	Université Catholique de Louvain		2
Andreas Vesalius	Università degli Studi di Padova and Université Catholique de Louvain	1537	105089

According to our current on-line database, Gemma Frisius has 4 students and 105096 descendants.
We welcome any additional information.

Gerardus Mercator

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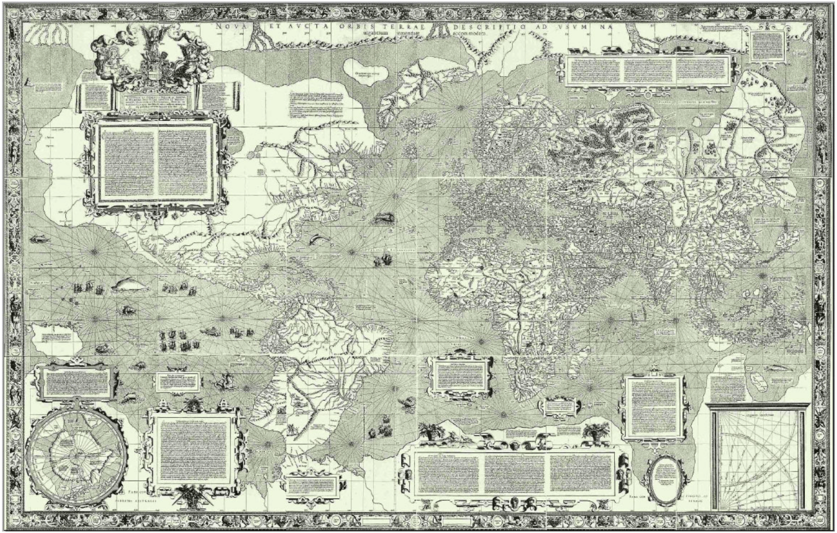
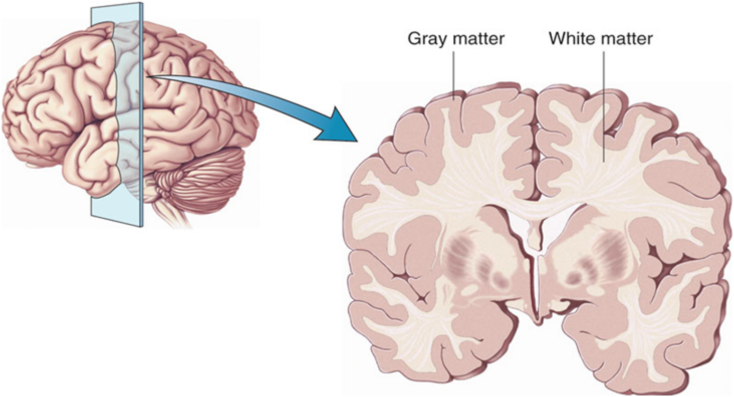


Gerardus Mercator

White Matter and Grey Matter (17th–18th centuries)

White matter: Generic term for "stuff" that appears white in freshly dissected brain.

Grey matter: Generic term for "stuff" that appears grey in a freshly dissected brain.



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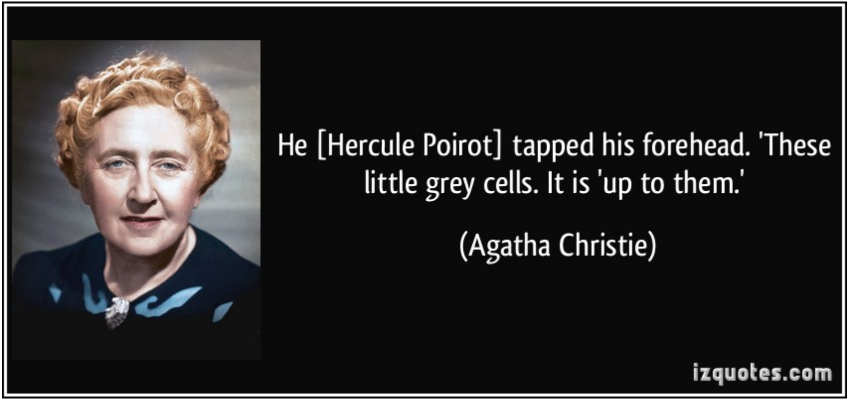

Structure to Function

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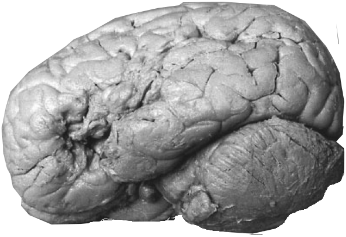
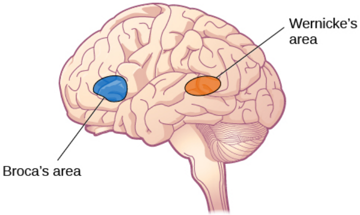


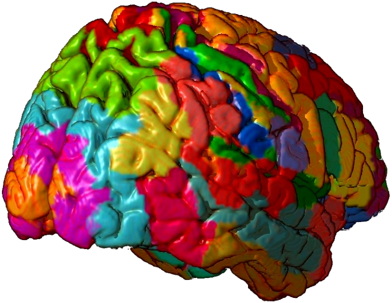
Structure to Function

- Broca's area (1861): production of speech and language
- Wernicke's area (1874): comprehension of spoken and written word



Brodmann Areas (1909)

Based on the cytoarchitectural organization of neurons Brodmann observed in the cerebral cortex using Nissl staining.



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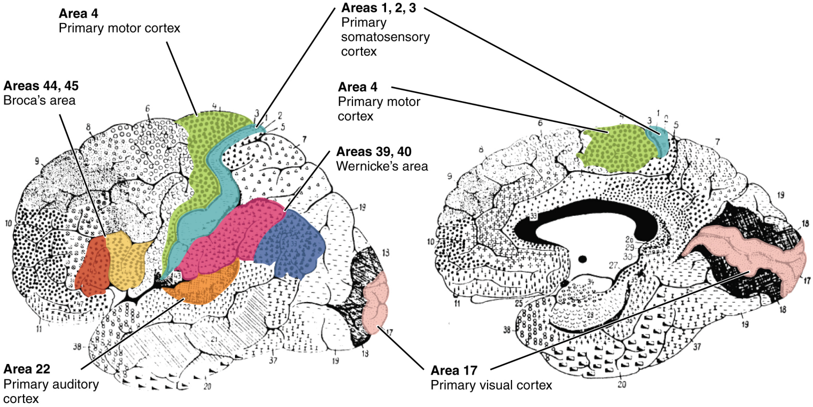
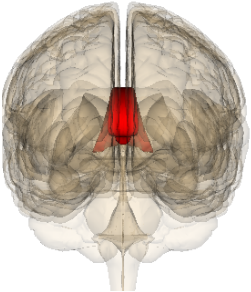


Brodmann's cytotechtonic map (1909): Lateral surface

Brodmann's cytotechtonic map (1909): Medial surface

Left and Right Brains (1960s)

- If the two hemispheres of the brain are separated by severing the corpus callosum,
  - information transfer between the hemispheres ceases,
  - an individual has two functionally different brains.



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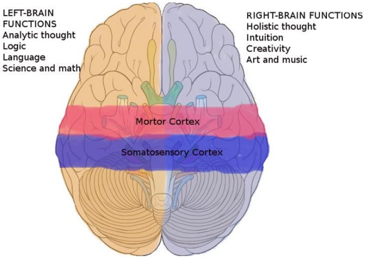

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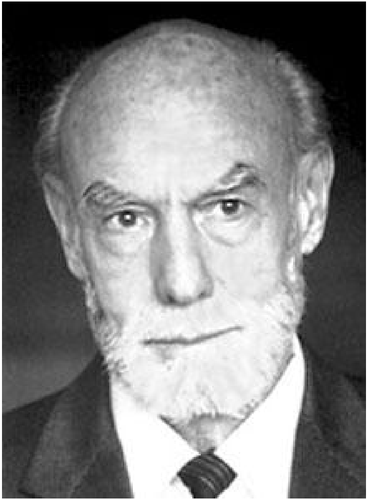
- Roger Sperry received the Nobel Prize in 1981.



"The great pleasure and feeling in my right brain is more than my left brain can find the words to tell you."

Left and Right Brains in Culture

The New York Times Magazine/September 9,1973

Two astonishingly different persons inhabit our heads

We are left-brained or right-brained

By Maya Pines

Two very different persons inhabit our heads, residing in the left and right hemispheres of our brains, the twin shells that cover the central brain stem. One of them is verbal, analytic, dominant. The other is artistic but mute, and still almost totally mysterious.

This nonspeaking side of the human brain—the right hemisphere—is now the focus of intensive research by brain scientists. This sudden surge of interest is probably no accident at a time when Yoga, Arica, Tibetan exercises and other nonverbal disciplines are enjoying such a vogue. Some re-

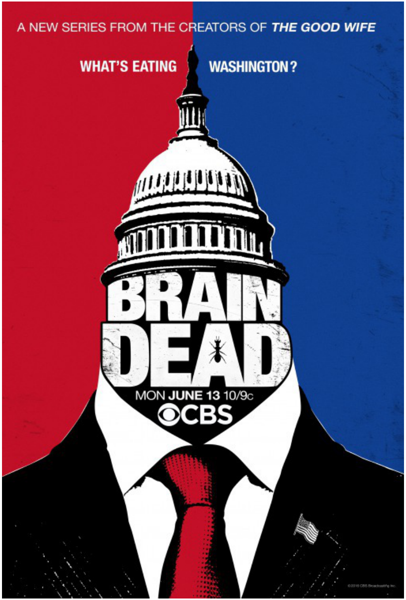
ample, those concerned with vision—to find their way through a tangle of other nerve fibers, even when obstacles are placed in their path, and somehow connect with the appropriate cells so as to reach specific terminals in the visual cortex. Next, he began to study visual perception and memory. He wanted to find out what happened when an animal learned certain discriminations that involved the visual cortex—when it learned, for instance, to push a panel marked with a circle rather than a square. Where in its brain was that knowledge stored?

He put the question to a young graduate student, suggesting that he investigate how cats that

between a circle and a square, knowing that the information they acquired would go to only one hemisphere. When he switched their eye patches to cover their trained eyes, however, the cats performed just as well as before. Their memory of this skill was intact. This meant either that the knowledge was stored in the central brain stem, well below the twin hemispheres, or that the knowledge acquired by one hemisphere had somehow been transmitted to the other.

"Obviously the *corpus callosum* was the next thing to test," recalls Dr. Myers. "But from the available evidence, cutting it would have no effect. If the surgery is properly done, the animals are

Left and Right Brains in Culture



Left and Right Brains in Culture

Are You More Right-Brained Or Left-Brained?

Research says it doesn't exist, but let's see where your personality falls.

Erin La Rosa
BuzzFeed Staff

justtransparentthings.tumblr.com

Check off all that apply:

- [ ] 1. You're better with faces than names.

Left and Right Brains in Culture

LIVESCIENCE NEWS TECH HEALTH PLANET EARTH SPACE STRANGE NEWS ANI

Left Brain vs. Right: It's a Myth, Research Finds

By Christopher Wanjek | September 3, 2013 12:21pm ET

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BAD MEDICINE CHRISTOPHER WANJEK COLUMNIST

The idea that one side of the brain is dominant is a myth, researchers say.

Credit: Human brain image via Shutterstock

Parts of the Brain (Now)

The Brain: Structure and Function (Video, 13:55)

Automated Parcellation of the Human Brain

NATURE | ARTICLE

日本語要約

A multi-modal parcellation of human cerebral cortex

Matthew F. Glasser, Timothy S. Coalson, Emma C. Robinson, Carl D. Hacker, John Harwell, Essa Yacoub, Kamil Ugurbil, Jesper Andersson, Christian F. Beckmann, Mark Jenkinson, Stephen M. Smith & David C. Van Essen

Affiliations | Contributions | Corresponding authors

Nature **536**, 171–178 (11 August 2016) | doi:10.1038/nature18933
Received 12 November 2015 | Accepted 15 June 2016 | Published online 20 July 2016

NATURE | NEWS

Human brain mapped in unprecedented detail

Nearly 100 previously unidentified brain areas revealed by examination of the cerebral cortex.

Linda Geddes

20 July 2016

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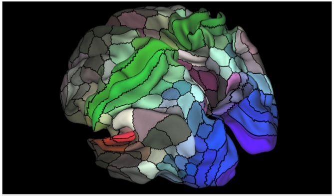

Matthew F. Glasser, David C. Van Essen

Researchers have divided the brain into discrete areas based on structure and function.

(Video, 2")

Brain Structure to Graphs

Table 3
Matrix of connections in visual cortex

From: \ To:	V1	V2	V3	VP	V3A	V4	VOT	V4t	MT	FST	PITd	PIT	PITv	CITd	CIT	CITv	AITd	AITv	STPp	STP	STPa	TF	TH	MSTd	MSTl	PO	PIP	LIP	VIP	MIP	MDP	DP	7a	FEF	46
	OCCIPITAL									TEMPORAL														PARIETAL										FRONTAL	
V1		+	+	.	+	+	.	NR	+	.	.		.	.		.	.	.	.		.	.	.	.	?	+	+	.	.	.	.	.	.	.	.
V2	+		+	+	+	+	+	+	+	+	.		.	.		.	.	.	.		.	.	.	+	+	+	+	.	+	.	.	.	.	?	.
V3	+	+			+	+	.	+	+	+	.		.	.		.	.	.	.		.	+	.	+	.	+	+	+	+	.	.		.	?	.
VP	.	+	+		+	+	+	.	+	+	.		.	.		.	.	.	.		.	+	.	+	.	+	+		+	.	.		.	?	.
V3A	+	+	+	+		+			+	+	.		.	.		.	.	.	.		.	.	.	+	+	+				.	.	+	.	?	.
V4	+	+	+	+	+			+	+	+	+		+	+		+	.	+	.		.	+	+	.	.	.	+	+	.	.	.	+	.	?	+
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46	.	.	.	.	.					.					+		+		+		+	+	+	.								+	+	+	

This table is a connectivity matrix for interconnections between visual cortical areas in the macaque. Each row shows whether the area listed on the left sends outputs to the areas listed along the top. Conversely, each column shows whether the area listed on the top receives inputs from the areas listed along the left. Large plus symbols (+) indicate a pathway that has been reported in 1 or more full-length manuscripts; small plus symbols indicate pathways identified only in abstracts or unpublished studies. Specific citations are listed in Table 5. Dots (·) indicate pathways explicitly tested and found to be absent. Blanks indicate pathways not carefully tested for. Question marks (?) denote pathways whose existence is uncertain owing to conflicting reports in the literature. "NR" and "NR?" indicate nonreciprocal pathways, i.e., connections absent in the indicated direction even though the reciprocal connection has been reported. Shaded boxes along the diagonal represent intrinsic circuitry that exists within each area; these are not included among the pathways tabulated in the following table.

Distributed Hierarchical in the Primate Cerebral Cortex, Daniel J. Felleman and David C. Van Essen, Cereb. Cortex, 1: 1–47, 1991.

Brain Structure to Graphs

Neuroinformatics
June 2004, Volume 2, Issue 2, pp 145–162

The small world of the cerebral cortex

Olaf Sporns ✉, Jonathan D. Zwi

Review Article

DOI: 10.1385/NI:2:2:145

Cite this article as:

Sporns, O. & Zwi, J.D. Neuroinform (2004) 2: 145. doi:10.1385/NI:2:2:145

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Cells in the Brain (Late 19th and early 20th Century)

Cell theory: Cell is the fundamental unit of all living organisms (Video, 1:40")

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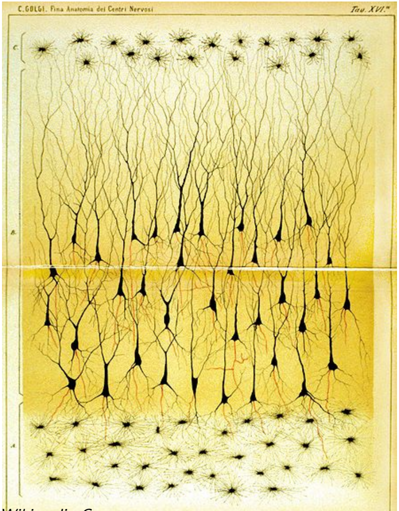
- Cajal: catalogued many different types of nerve cells.



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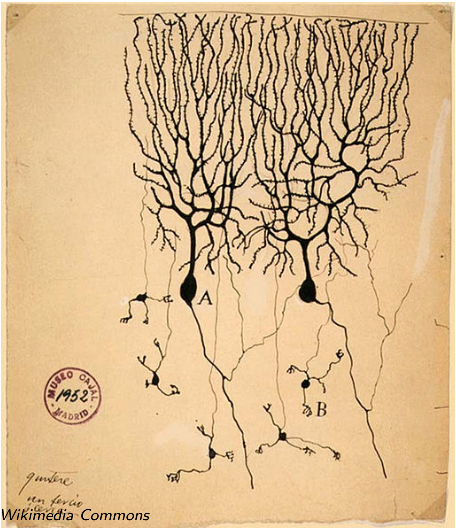

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Reticular Theory vs. Neuron Doctrine

- "Neuron" coined by Waldeyer in 1891.
- In 1896, Rudolph Albert von Kolliker coined the term "axon" to describe the long slender cables that transmit signals away from cell bodies.
- In 1889, William His used "dendrites" to name the thin branching fibers that ferry signals toward the cell body.

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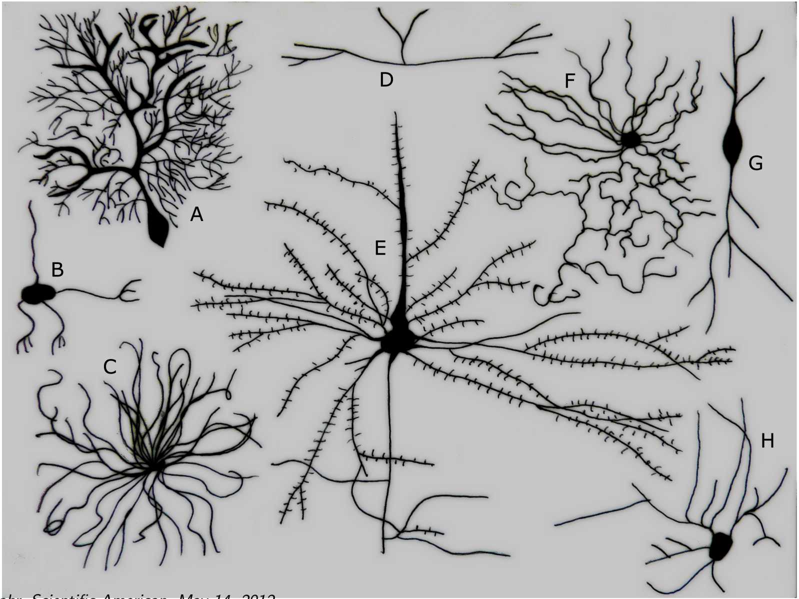
- Both Golgi and Cajal received the Nobel prize in Physiology or Medicine in 1906.

Cells in the Brain



Ferris Jabr, Scientific American, May 14, 2012

Cells in the Brain

Types of Brain Cells (Video, 18:54")

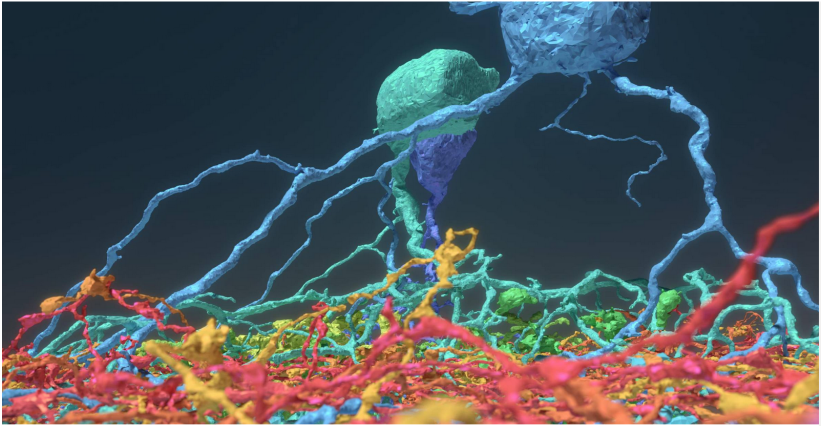
Types of Neurons

- 100s of types of neurons, differentiated by structure, function, genetics ...
- neuromorpho.org: archive of digitally reconstructed neurons.

Welcome to NeuroLex, the Neuroscience Lexicon.

A dynamic lexicon of 34,533 neuroscience terms , including 754 neurons and 1303 parts of the nervous system supported by The Neuroscience Information Framework and the International Neuroinformatics Coordinating Facility

Types of Neurons



Princeton researchers crowdsource brain mapping with gamers, discover six new neuron types

Liz Fuller-Wright, Office of Communications

May 17, 2018 11 a.m.

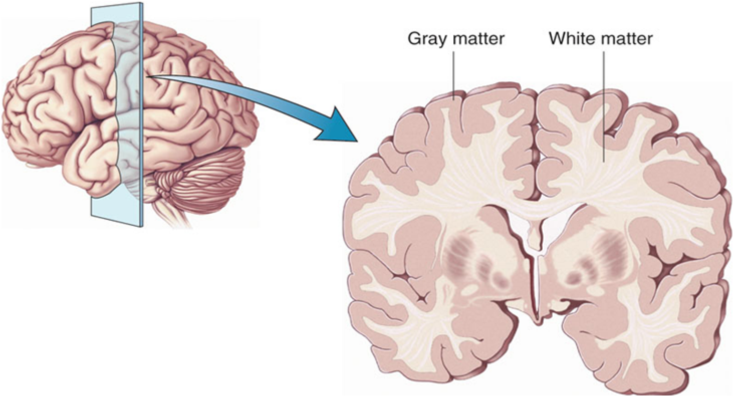
By turning a time-intensive research problem into an interactive game, Princeton neuroscientist Sebastian Seung has built an unprecedented data set of neurons, which he is now turning over to the public via the Eyewire Museum. These 17 retinal neurons, mapped by Eyewire gamers, include ganglion cell types in blue and green and amacrine cells in yellow and red.

Image by Alex Norton, Eyewire

White Matter and Grey Matter (17th–18th centuries)

White matter Generic term for "stuff" that appears white in freshly dissected brain.

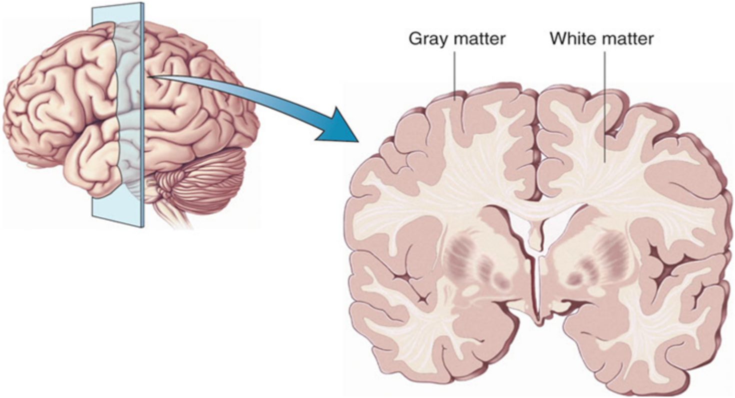
Grey matter Generic term for "stuff" that appears grey in a freshly dissected brain.



White Matter and Grey Matter (17th–18th centuries)

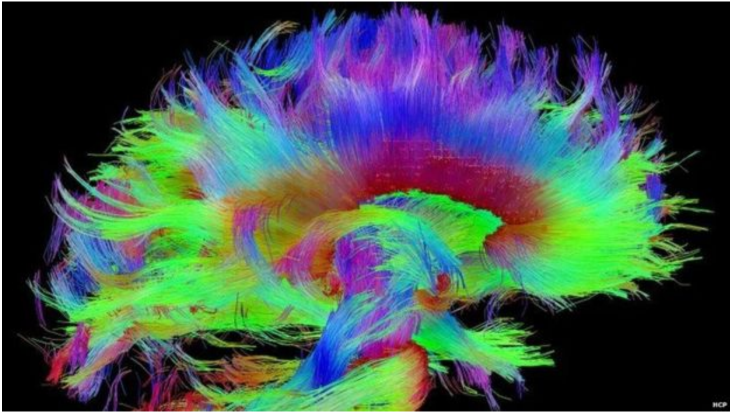
White matter: Generic term for ~~"stuff"~~ a collection of axons, which appear white in freshly dissected brain.

Grey matter: Generic term for ~~"stuff"~~ a collection of neuronal cell bodies, which appear grey in a freshly dissected brain.



Brain Structure to Graphs

- Diffusion tensor imaging.
- Tracking white matter (axon) bundles to connect voxels.
- Massive graphs: 15M nodes, 50M edges.

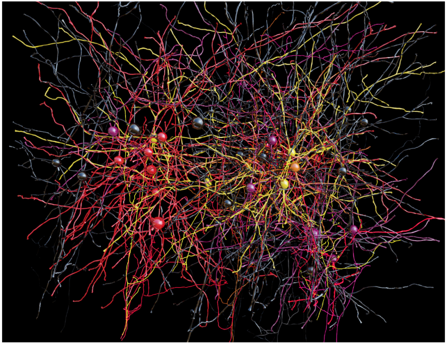


Research on largest network of cortical neurons to date published in Nature

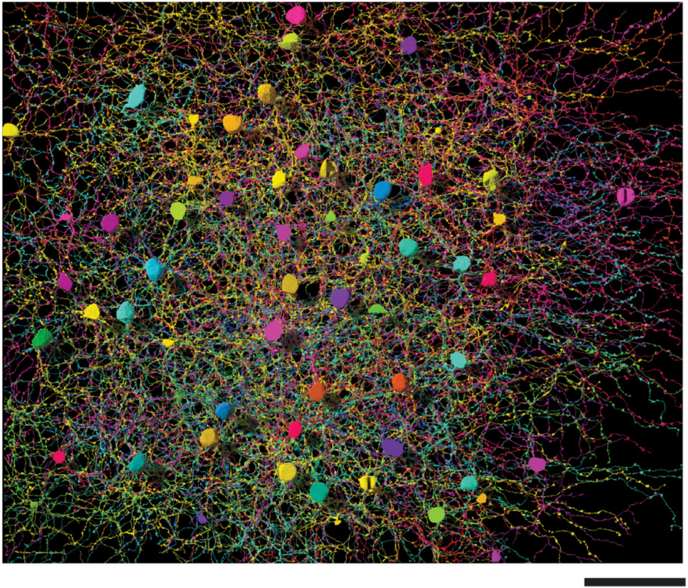
Robust network of connections between neurons performing similar tasks shows fundamentals of how brain circuits are wired

March 28, 2016 | Download PDF

Even the simplest networks of neurons in the brain are composed of millions of connections, and examining these vast networks is critical to understanding how the brain works. An international team of researchers, led by R. Clay Reid, Wei Chung Allen Lee and Vincent Bonin from the Allen Institute for Brain Science, Harvard Medical School and Neuro-Electronics Research Flanders (NERF), respectively, has published the largest network to date of connections between neurons in the cortex, where high-level processing occurs, and have revealed several crucial elements of how networks in the brain are organized. The results are published this week in the journal *Nature*.



Anatomy and function of an excitatory network in the visual cortex, Lee et al., Nature, 532:370–374, 2016.



Space–time wiring specificity supports direction selectivity in the retina, Kim et al., Nature, 509:331–336, 2014.

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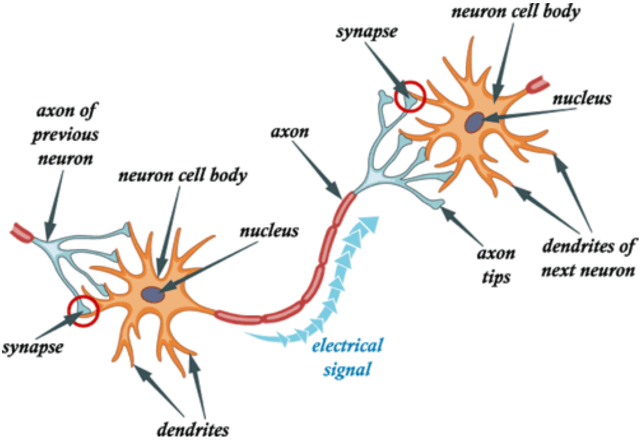
Cellular Communication: Neuron Firing

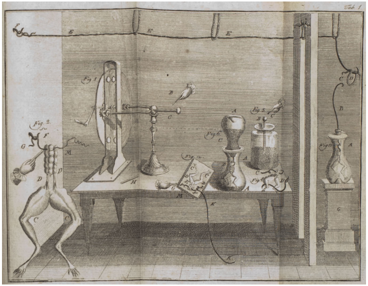


Neuron, YouTube, 11:20"

www.jasonshen.com

Otto Loewi (1873–1961)

- Galvani showed that electric stimulation of sciatic nerve causes muscles in frog legs to twitch (1780).
- How do nerves communicate with muscles: electricity or chemicals?



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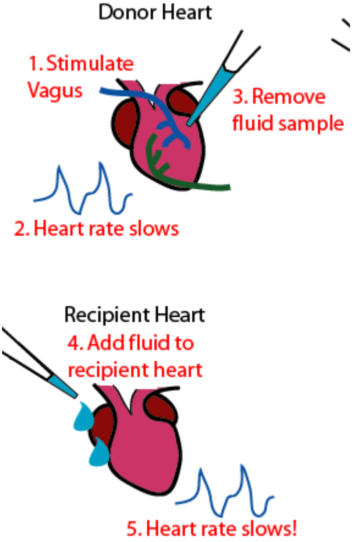

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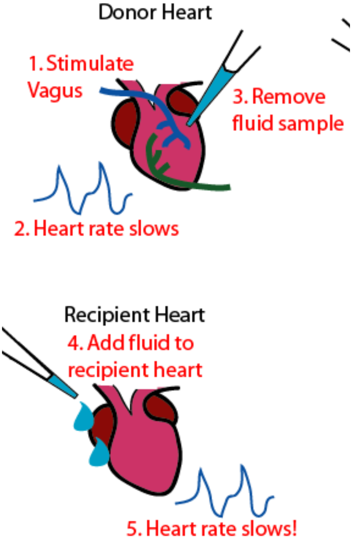
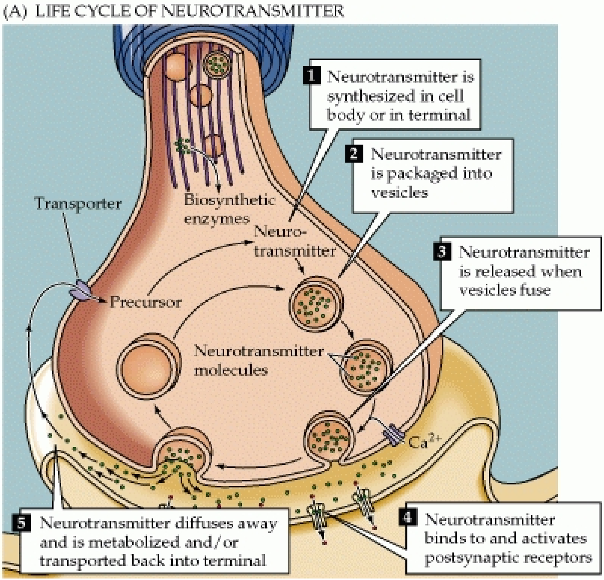
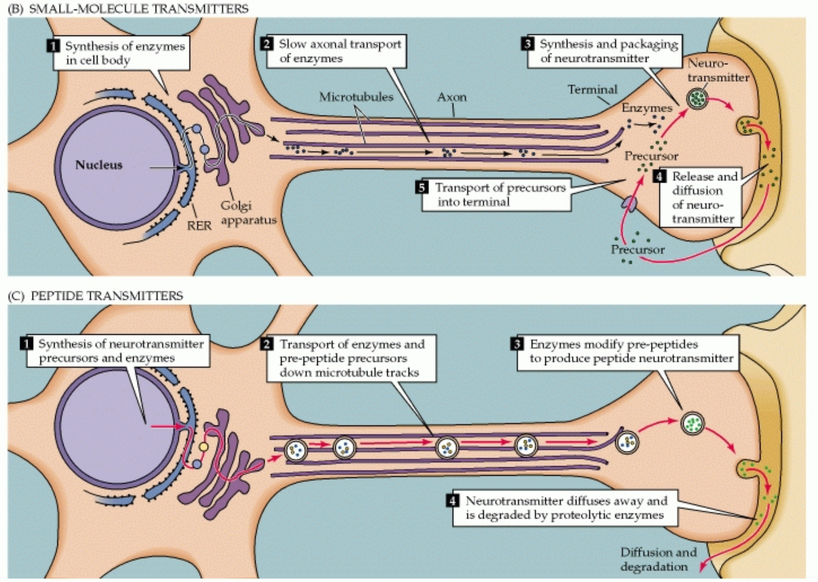
- Loewi settled this question through his discovery of *vagusstoff* (1921).
- Later identified as acetylcholine, which had been discovered in 1914 by Sir Henry Dale. *The first neurotransmitter.*
- Loewi and Dale received the Nobel Prize in 1936.



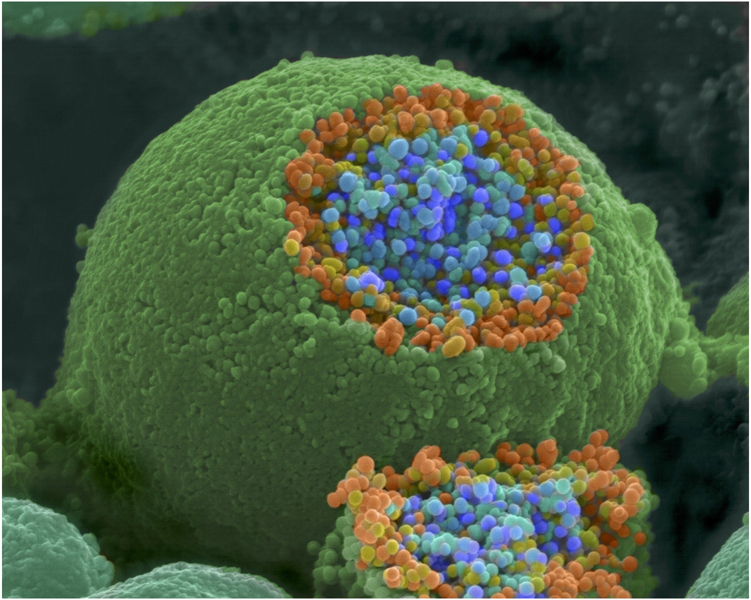
Neurotransmitters



Neurotransmitters



Neurotransmitters



Neurotransmitters

TABLE 47-1

Neurotransmitters and Their Relationship to Mental Disorders

NEUROTRANSMITTER	PHYSIOLOGIC EFFECTS	RELATIONSHIP TO MENTAL DISORDERS
Acetylcholine	Sleep/wake cycle. Signals muscles to become active.	Decreased in Alzheimer's and Parkinson's diseases.
Dopamine	Controls complex movements, cognition, motivation, and pleasure. Regulates emotional responses.	Increased in schizophrenia and mania. Decreased in depression and Parkinson's.
Norepinephrine	Affects attention, learning, memory, and regulation of mood, sleep, and wakefulness.	Decreased in depression. Increased in schizophrenia, mania, and anxiety.
Serotonin	Affects sleep and wakefulness, especially falling asleep. Affects mood and thought processes.	Probably plays a role in thought disorders of schizophrenia. Decreased in depression. Possibly decreased in anxiety and obsessive-compulsive disorder.
Gamma-aminobutyric acid (GABA)	Amino acid that modulates other neurotransmitters.	Decreased in anxiety and schizophrenia.

Alzheimer's Disease

Mechanisms and secrets of Alzheimer's disease: exploring the brain, Video, 6:26"

Rita Levi-Montalcini (1909–2012)

- M.D. at University of Turin (1936).
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- Secret lab in bedroom to study nerve growth in chicken embryos (WWII).

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- Isolated nerve growth factor (NGF) by observing that cancerous tissues caused extremely rapid growth of nerve cells in chicken embryos (1952). *First growth factor discovered.*

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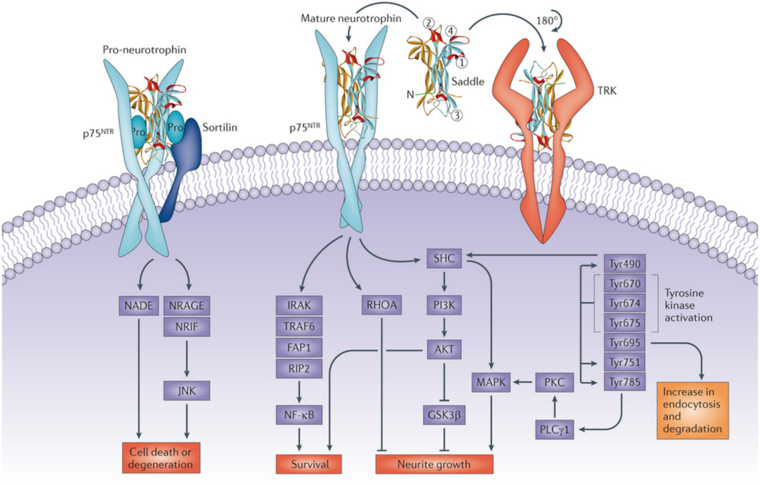
- Received Nobel prize (with Stanley Cohen, 1986).

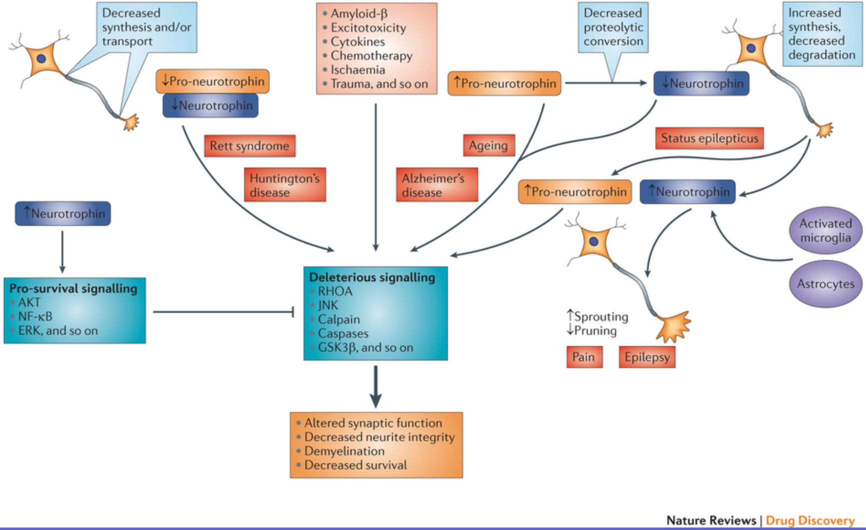
Neurotrophins

Family of proteins that induce the survival, development, and function of neurons.

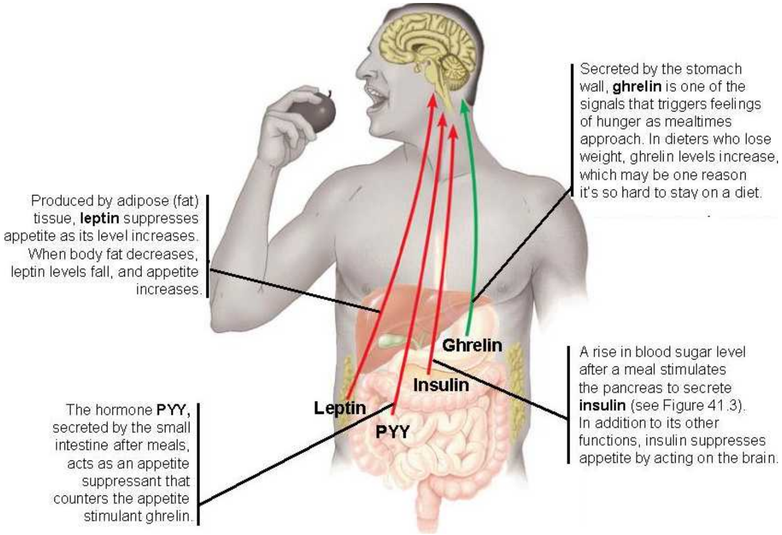


Neurotrophins

Changes in neurotrophin levels or in the ratio of pro-neurotrophin to mature neurotrophin can cause and/or contribute to numerous diseases.

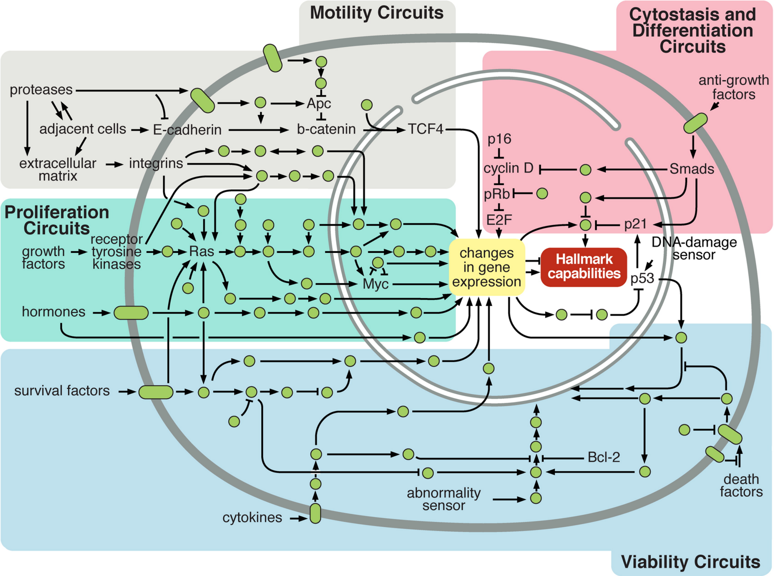


Cellular Communication: Hunger Response



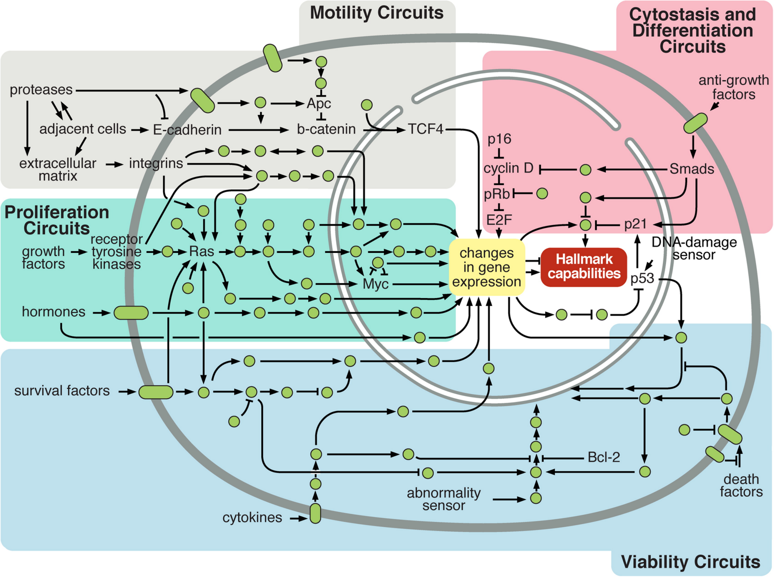
www.barbellmedicine.com

Cellular Response to External Signals

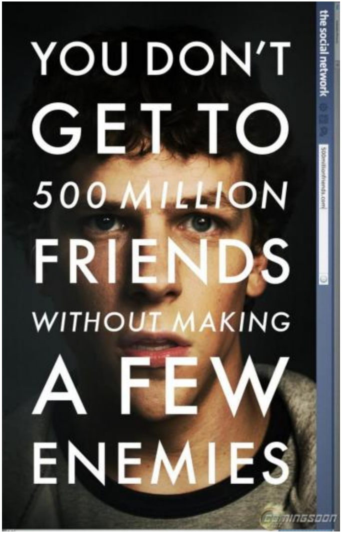


Hanahan and Wienberg. Hallmarks of cancer: the next generation. Cell, 2011.

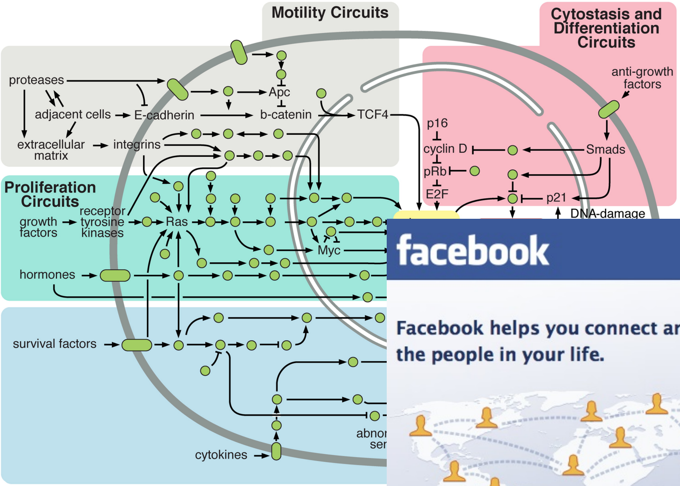
A Cell is Like



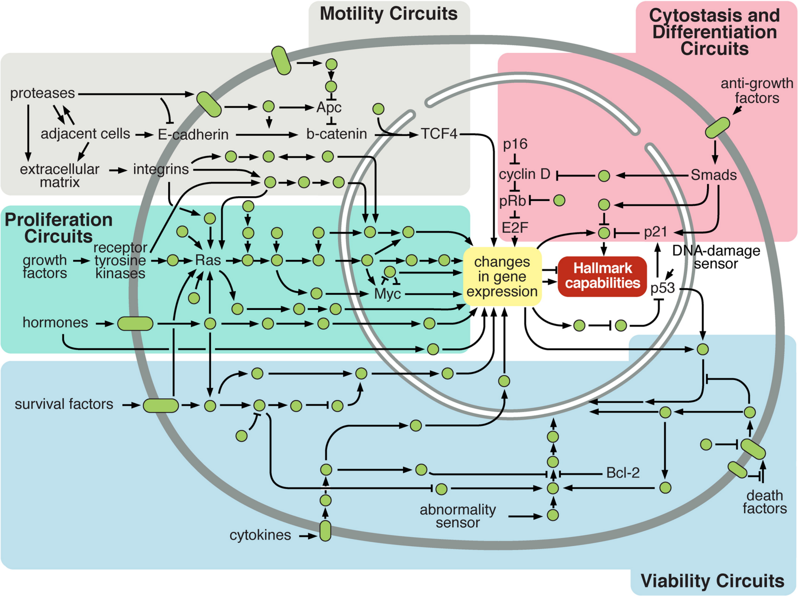
A Cell is Like



A Cell is Like facebook



Network is Complex



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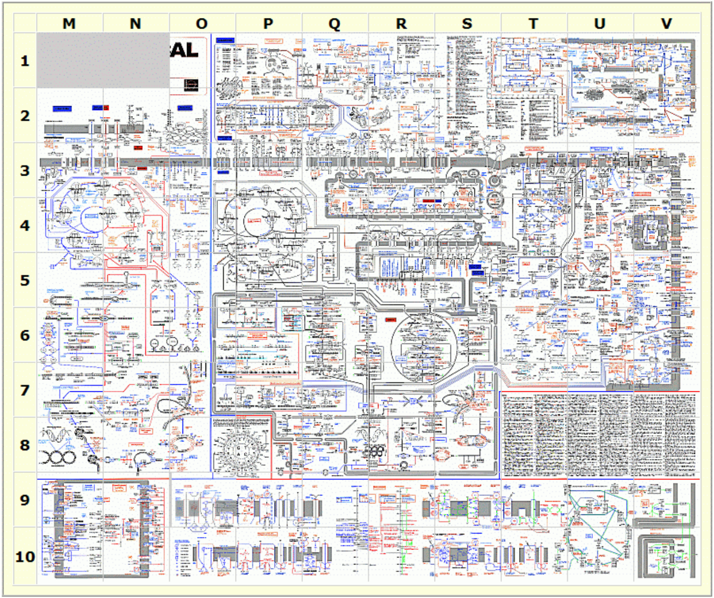
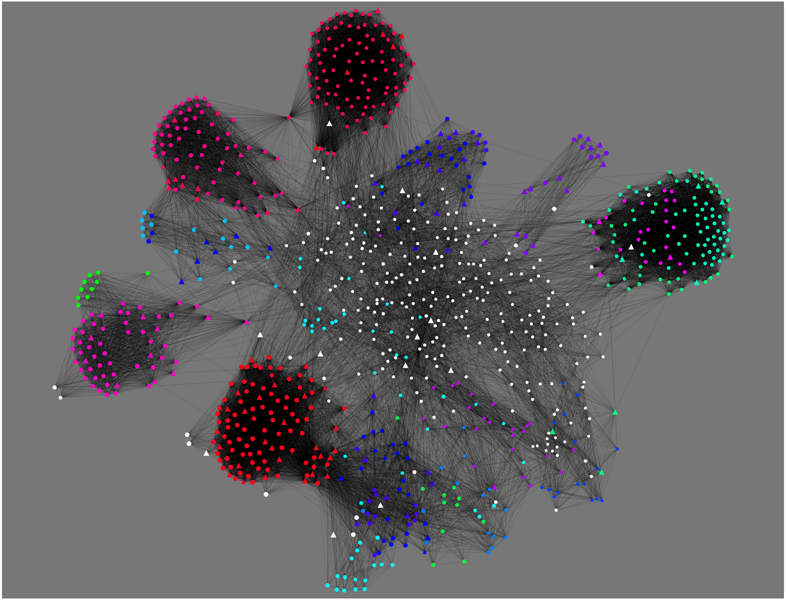
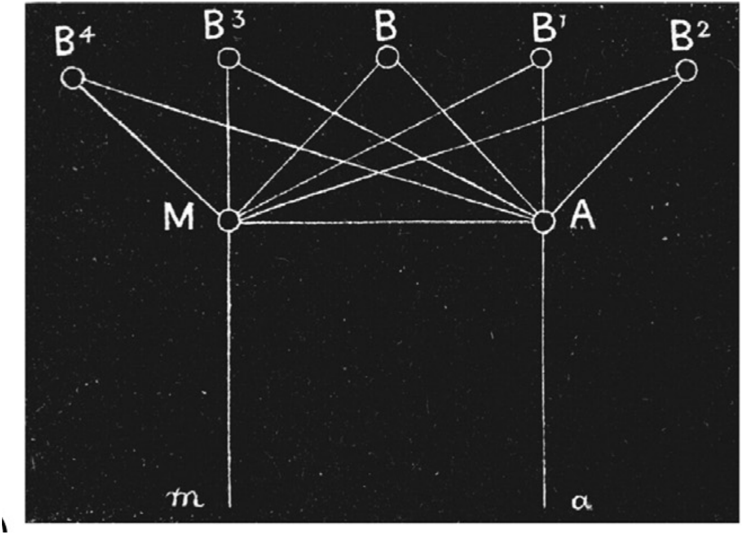


Network is Complex but Very Poorly Understood

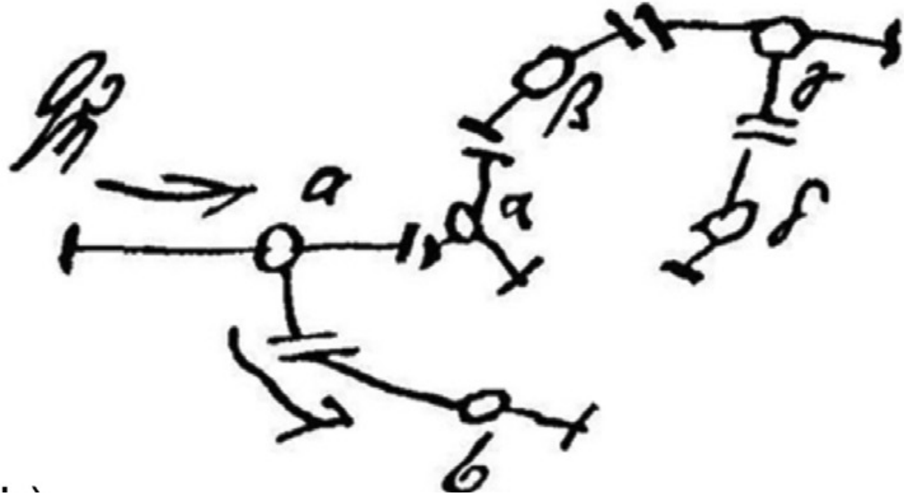


Early Brain Graphs



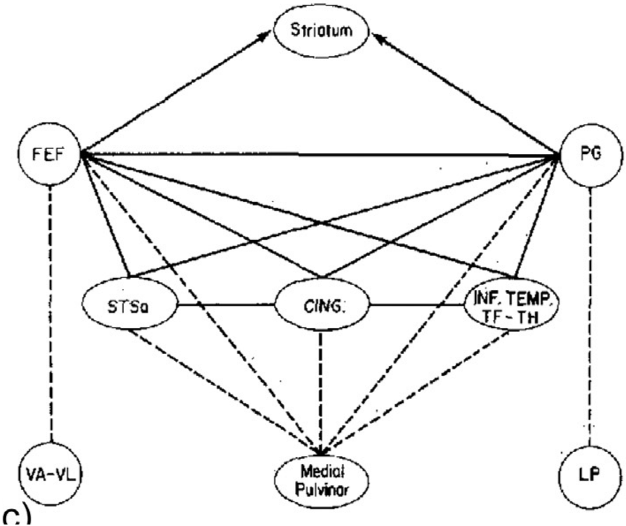
Large-scale human network for language (Lichtheim, 1885)

Early Brain Graphs



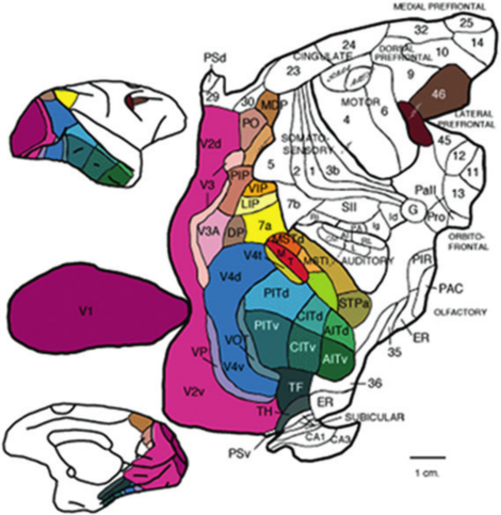
Neuronal network for psychoanalysis (Freud, 1891, 1895)

Early Brain Graphs



Hub-and-spoke model of spatial attention (Mesulam, 1990)

Dawn of Connectomics



Macaque visual cortex (Felleman and van Essen, 1991)

Dawn of Connectomics

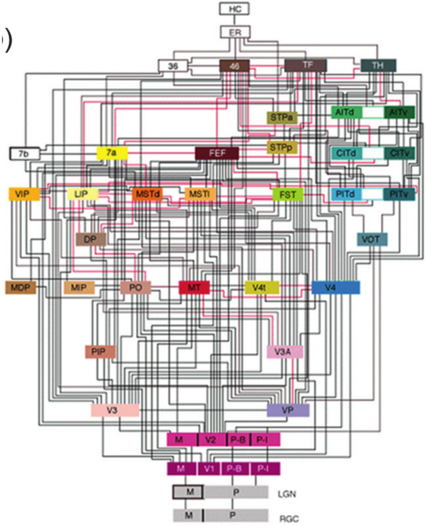
Table 3
Matrix of connections in visual cortex

	OCCIPITAL									TEMPORAL														PARIETAL										FRONTAL	
From: / To:	V1	V2	V3	VP	V3A	V4	VOT	V4t	MT	FST	PITd	PIT	PITv	CITd	CIT	CITv	AITd	AITv	STPp	STP	STPa	TF	TH	MSTd	MSTl	PO	PIP	LIP	VIP	MIP	MDP	DP	7a	FEF	46
V1		+	+	.	+	+	.	NR	+	.	.		.	.		.	.	.	.		.	.	.	.	?	+	+	.	.	.	.	.	.	.	.
V2	+		+	+	+	+	+	+	+	+	.		.	.		.	.	.	.		.	.	.	+	+	+	+	.	+	.	.	.	.	?	.
V3	+	+			+	+	.	+	+	+	.		.	.		.	.	.	.		.	+	.	+	.	+	+	+	+	.	.		.	?	.
VP	.	+	+		+	+	+	.	+	+	.		.	.		.	.	.	.		.	+	.	+	.	+	+		+	.	.		.	?	.
V3A	+	+	+	+		+			+	+	.		.	.		.	.	.	.		.	.	.	+	+	+				.	.	+	.	?	.
V4	+	+	+	+	+			+	+	+	+		+	+		+	.	+	.		.	+	+	.	.	.	+	+	.	.	.	+	.	?	+
VOT	.	+	.	+		+					+		+																						
V4t	+		+	.		+			+	+														NR?	+	+								?	
MT	+	+	+	+	+	+		+		+	.		.	.		.	.	.	.		.	.	.	+	+	?	+	+	+	.	.	.	.	+	?
FST	.	NR?	+	NR?	+	+		+	+			+		.		.	.	.	+			+		+	+	.	.	+	+				+	+	.
PITd	.	.	.	.	.	+			.							+	+	+							.	.	.	.	.				.		
PIT										+														+										+	+
PITv	.	.	.	.	.	+			.							+		+							.	.	.						.		
CITd	.	.	.	.	.	+			.				+				+	+							.	.	.	.	.				.		
CIT																																		+	+
CITv	.	.	.	.	.	+			.				+				+	+						.	.	.	.	.	.				.		
AITd	.	.	.	.	.	.			.	.			+			+								.	.	.	.	.	.	.	.		+	+	+
AITv	.	.	.	.	.	+			.	.			+			+					.	+	+	.	.	.	.	.	.	.	.				
STPp	.	.	.	.	.	.			.	+					+		.				+	+	+	+	+	.	.	.	.	.	.			+	+
STP																																	+		
STPa	.	.	.	.	.	.			.								+	.	+			+	+			.	.	.	.	.	.				+
TF	.	.	+	+	.	+			.	+			+			+	+	+	+		+			+		.	.		.	.	.		+		+
TH	.	.	.	.	.	+			.				+		+		+	+	+		+			.	.	.	.	.	.	.	.		+		+
MSTd	.	+	+	+	+	.		+	+	+		+		.		.	.	.	+							+		+	+			+	+	+	
MSTl	NR	+	.	.	+	.		NR?	+	+	.	.	.	.		.	.	.	+							+	.		+			NR?	NR?	+	
PO	+					.			+	.	.		.	.		.	.	.	.		.	.	.	+	+			+	+			+	+	?	
PIP	+		+	+		+			+		.		.	.		.	.	.	.		.					+						+	+		
LIP	.		+	+	+	+			+	+	.		+	.		.	.	.				+	.	+	+	+			+			+	+	+	+
VIP	.		+						+	+	.		.	.		.	.	.						+	+	+		+					+	+	
MIP	.	.	.	.	.	.			.	.	.		.	.		.	.	.						.	.	+							+		
MDP	.	.	.	.	.	.			.	.	.		.	.		.	.	.						.	.	+							+		
DP	.	.	.	.	+	+			.	+	.		.	.		.	.	.	.		.	.	.	+	+	+	+	+					+		+
7a	.	.	.	.	.	.			.		.		.	.		.	+			+		+	+	+	?	+		+				+		+	+
FEF	.								?	+					+		+		+					+	+	+		+	+			+	+		+
46	.	.	.	.	.					.					+		+		+		+	+	+	.								+	+	+	

This table is a connectivity matrix for interconnections between visual cortical areas in the macaque. Each row shows whether the area listed on the left sends outputs to the areas listed along the top. Conversely, each column shows whether the area listed on the top receives inputs from the areas listed along the left. Large plus symbols (+) indicate a pathway that has been reported in 1 or more full-length manuscripts; small plus symbols indicate pathways identified only in abstracts or unpublished studies. Specific citations are listed in Table 5. Dots (·) indicate pathways explicitly tested and found to be absent. Blanks indicate pathways not carefully tested for. Question marks (?) denote pathways whose existence is uncertain owing to conflicting reports in the literature. "NR" and "NR?" indicate nonreciprocal pathways, i.e., connections absent in the indicated direction even though the reciprocal connection has been reported. Shaded boxes along the diagonal represent intrinsic circuitry that exists within each area; these are not included among the pathways tabulated in the following table.

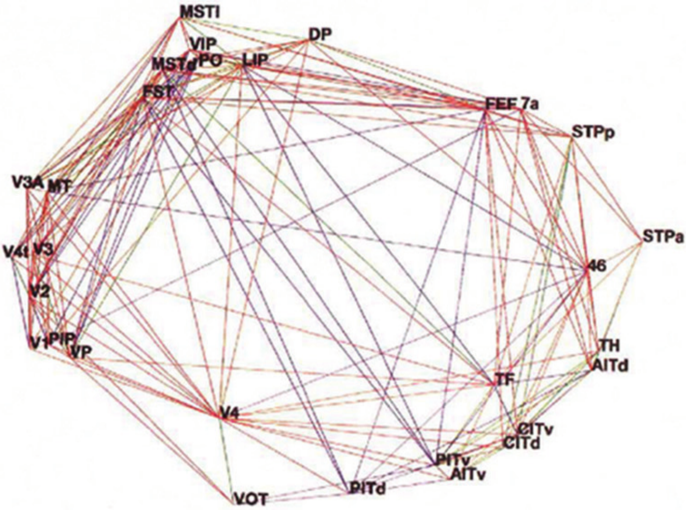
Tract-tracing in the macaque visual cortex (Felleman and van Essen, 1991)

Dawn of Connectomics



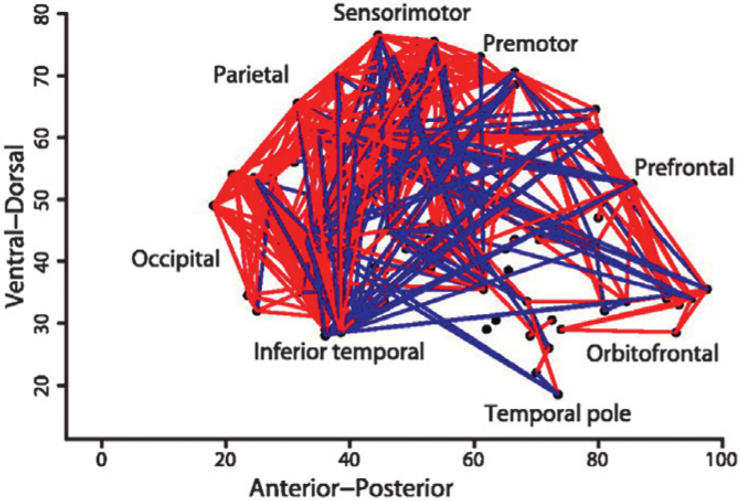
Wiring diagram of macaque connectome (Felleman and van Essen, 1991)

Dawn of Connectomics



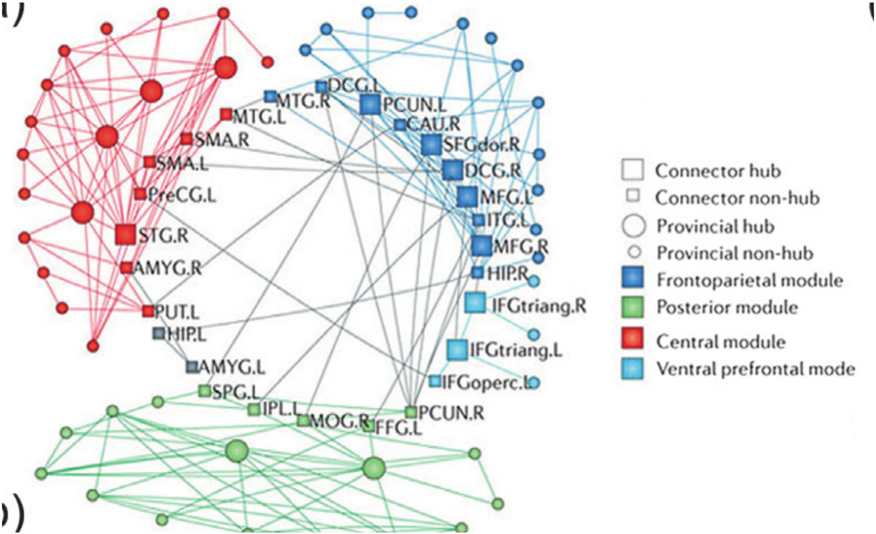
Topological representation of macaque connectome (Young, 1992)

Human Connectomics



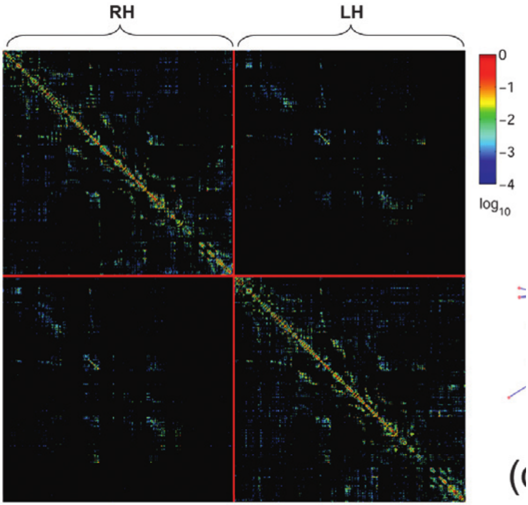
Functional connectivity network from functional MRI data

Human Connectomics



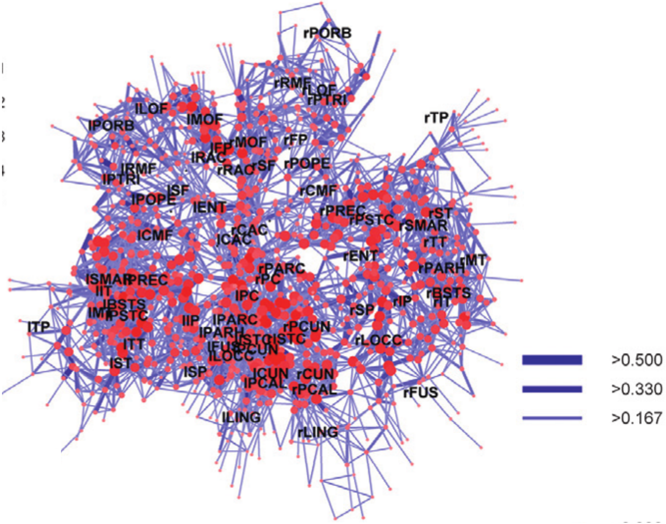
Modular organisation of network

Human Connectomics



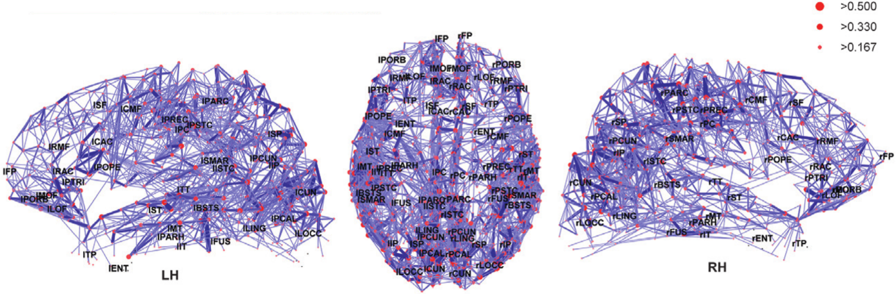
Connectivity network from diffusion MRI data

Human Connectomics



Toplogical layout of network

Human Connectomics



Anatomical layout of network