# Introduction to Cognitive Neuroscience

## What is cognitive neuroscience?

*Neuroscience* is a physical science -- it seeks to understand physical mechanisms of the nervous system.

*Cognitive neuroscience* is the branch of neuroscience that seeks to understand the mechanisms of the nervous system that are directly related to cognitive (mental) processes. These mechanisms are thought to reside in the brain. Because cognition refers to functions of the mind, we must begin our study of cognitive neuroscience by first examining the relation between the mind and the brain.

The question of how the mind and brain are related is called the *mind-brain problem*. It taps into some deep philosophical issues.

## Ontology

*Ontology* is the philosophical study of the nature of reality. It addresses the question of "what exists". A basic question of ontology is whether there is more than one order (domain, realm) of reality.

Most people, and all scientists, agree that there is a physical order of reality. It includes all entities and effects that are described by physical science. The brains of humans and other animals are such entities. Within the brain is a physical (neural) order.

Controversy arises in deciding whether the physical is the only realm of existence. Is the mental order separate from, and independent of, the physical order?

What makes the mind-brain problem difficult is our personal experience (subjective awareness). Experiential descriptions are usually called "mental", but it is difficult to determine whether mental, or more currently "cognitive", descriptions refer to a unique and separate domain of existence, or simply are a roundabout way of referring to the physical domain.

The *philosophy of mind* is a branch of philosophy that studies the nature of the mind, and its relationship to the physical body, particularly the brain. The *mind-brain problem* (formerly, the mind-body problem) is a central topic in the philosophy of mind.

Although many well-developed philosophies of mind have been proposed over the centuries, there is still no generally agreed-upon solution to the mind-brain problem.

## Philosophy of mind

3 traditional approaches to the mind-brain problem:

1) *Dualism*: physical and mental are two fundamental domains of existence. The three main types of dualism differ in the causal relations they propose between physical and mental phenomena.

   a. *Interactionism*: there are physical effects caused by the mental realm and mental effects that have physical causes.

   b. *Epiphenomenalism*: causation only occurs in one direction, i.e. from physical to mental.

   c. *Parallelism*: mental and physical effects are related, but not causally. Mental and physical events are in direct correspondence, but do not cause one another.

2) *Idealism*: the fundamental domain of reality is the mental -- the physical world is the construction of the mind -- material objects have no existence except as the contents of perceptual states of the mind.

3) *Physicalism (materialism)*: the fundamental domain of reality is the physical. Mental events are essentially physical in nature.

   a. *Identity theory of mind (type physicalism)*: mental events are identical to physical events in the brain.

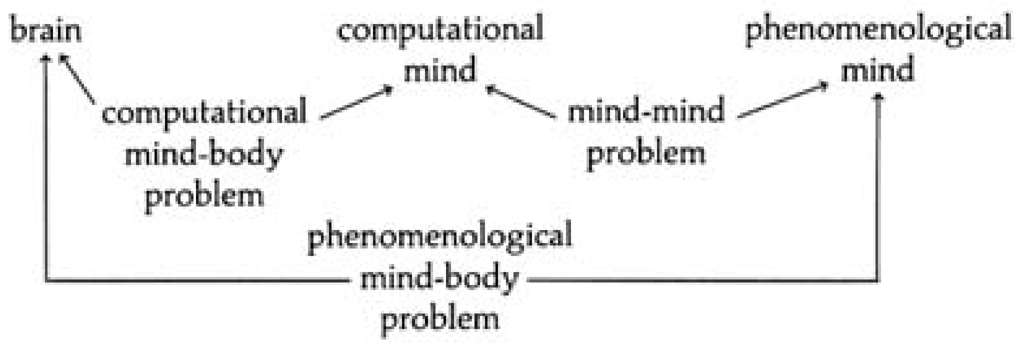
   b. *Eliminative materialism:* all mental events will eventually be described as physical events in the brain, but only with the elimination of "common-sense" descriptions of mental phenomena.

   c. *Behaviorism*: the "mind" is a hypothetical construct; mental events are descriptions of behavior, not "interior states".

   d. *Functionalism:* the mind is "what the brain does"; mental events are characterizations of physical states of the brain, describing their causal relations with other mental states, sensory inputs, and behavioral outputs. Includes the *computational theory of mind*.

   e. *Nonreductive physicalism:* mental states are physical states, but mental states cannot be reduced to behavior, brain states, or functional states.

## Phenomenological mind and computational mind




A functionalist approach to the mind-brain problem has been proposed by *Jackendoff* (1990), who distinguishes between:

(a) the *phenomenological* notion of mind, which pertains to the mind as the seat of conscious awareness.

and

(b) the *computational* notion of mind, which treats the mind as an information-bearing and information-processing system.

From this perspective, we can say that cognitive neuroscience studies the *computational mind-brain relation*.

It regards the computational mind as an abstract specification of functional organization in the nervous system.

## A matter of correlation

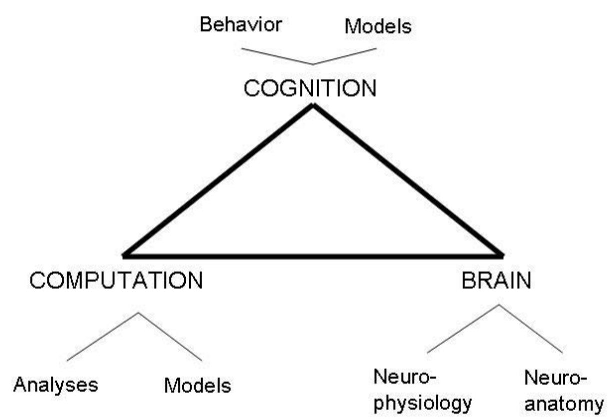
Even if we take a functionalist approach and reduce the mind-brain problem to the computational mind-brain problem, then we are still left with the problem that theories of the computational mind in cognitive science and theories of the brain in neuroscience represent two *independent systems of description*. Cognitive neuroscience has not developed to the point where it has established causal relations between cognitive phenomena and neural phenomena.

All science undergoes a natural progression from observation to correlation to causation. Cognitive neuroscience is largely still at the stage of correlation.

Even so, correlation is not a simple matter. It is difficult to know which neural entities correlate with which cognitive entities.

## The cognitive neuroscience triangle (Kosslyn & Koenig 1992)

To approach this problem, cognitive neuroscience attempts to establish correlations between cognitive phenomena and neural phenomena, using 3 major domains:
(a) cognition (behavior & models)
(b) brain (neurophysiology & neuroanatomy)
(c) computation (analyses & models)



We next consider how attempts to understand the relation between cognition and brain function in the field of neuropsychology have led to the concept of neural networks. Then we will consider how attempts to understand the computational basis of brain function in the field of artificial intelligence have also led to the concept of neural networks.

## The concept of “neural network” in neuropsychology

Neuroscience has been very successful at explaining the neural basis of low-level sensory and motor functions. These functions rely on the input and output systems of the nervous system, where discrete structural modules represent elemental sensory and motor components. This success has led to a reliance on modular explanations of brain function.

However, this *modular paradigm* fails to explain essential cognitive functions such as perception, attention, or memory.

The modular paradigm attempts to assign specific cognitive functions to individual brain modules. One problem with this approach is that it assumes that the different cognitive functions are separate entities.

This assumption is adequate for the cognitive psychologist, i.e. cognitive functions may be conceived as being distinct at the psychological level. However, it does not necessarily follow that these functions have separate neural substrates.

The assumption that there is a cortical module for every cognitive function has caused a great deal of confusion in cognitive neuroscience.

The concept of *networks* provides a vital alternative to the modular paradigm.

The network paradigm has taken centuries to develop. Even now it is not universally accepted, but its acceptance is rapidly growing.

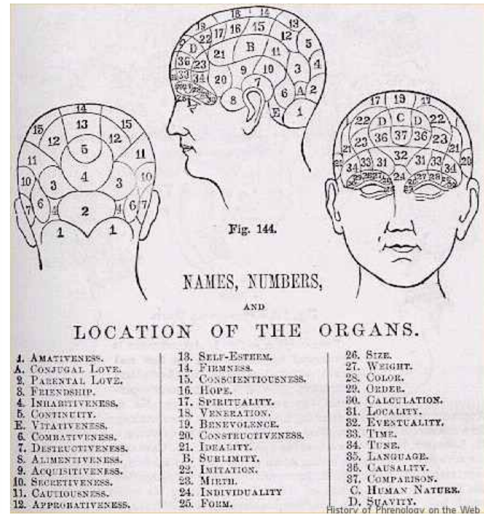
To understand the difference between the modular and network paradigms, it is necessary to examine the history of understanding the relation between brain function and cognition. This history has been dominated by two parallel trends: *localizationism* and *globalism*.

## Localizationism vs globalism


Historically, there has been a controversy for about 200 years in neuropsychology over the question of whether different mental functions are carried out by different parts of the brain (*localizationism*) or the brain works as a single, integrated whole (*globalism*).

## Phrenology


FIG. 1.1 ''Bumpology.'' George Cruikshank, 1826. The legend reads, ''Pores o'er the Cranial map with learned eyes/Eash rising hill and bumpy knoll descries/Here secret fires, and there deep mines of sense/His touch detects beneath each prominence.'' (Historical Library, Yale Medical Library.)




In the 17th & 18th centuries, the *theory of faculties* was dominant in psychology.

All psychological processes were understood as "faculties" of mind, incapable of further subdivision.

In 1796, Franz Joseph *Gall* began measuring bumps on the heads of Viennese residents. He postulated that the brain is a collection of centers corresponding to specific "faculties".

He thought that even very elaborate & abstract functions e.g. cautiousness, generosity, hope, were discretely localized to single areas of cerebral cortex.

Cranial bumps were thought to reflect development of cortical area underneath and consequently the corresponding mental trait.

This concept, later called *phrenology* by *Spurzheim*, represents an extreme expression of the localizationist view.

Incorrect assumptions:
a) cognitive functions are implemented by discrete cortical regions
b) development of a cognitive function increases the size of its region
c) enlargement of cortical regions causes expansion of the outer cranial surface

Correct assumptions:
a) mental abilities can be specified and analyzed
b) the cerebral cortex is important for mental ability
c) the brain is not a single, undifferentiated system

## Globalism

Phrenology was criticized by Pierre *Flourens* (1824) who found that mental functions are not localized, but that the brain acts as a whole for each function.

The Paris Academy of Sciences commissioned him to investigate the claim of Gall that character traits are localized in specific cortical regions.

He studied the effects of brain lesions on the behavior of pigeons.
The pigeons could recover after parts of the brain were removed, regardless of the location of the damage.

He concluded that the major brain divisions are responsible for different functions.
Cerebral cortex: perception, motricity, judgment
Cerebellum: equilibrium, motor coordination
Medulla: respiration, circulation

However, he found no localization of cognitive function within the cerebral cortex. He concluded that the cortex has *equipotentiality* for cognitive function: lost function with ablation does not depend on the location of damage, but only on the amount of tissue lost.

## The controversy continued

Later animal studies showed that different parts of the brain do have specific functions:

In 1870, Eduard *Hitzig* (assisted by Gustav *Fritsch*) supported the localizationist view based on evoked muscular responses from direct stimulation of the frontal lobe of the cortex of a dog.

In 1881, Hermann *Munk* removed parts of the occipital lobe of a dog's brain & found that it could still see but could no longer recognize objects.

Clinical evidence suggesting localization of function also appeared:

In 1861, Paul *Broca* showed that a lesion of the posterior third of the left inferior frontal gyrus causes a motor speech disturbance without affecting understanding of speech. He believed that the "motor images of words" are localized in this part of the brain.

In 1874, Carl *Wernicke* described a patient who had difficulty comprehending speech after damage to the left superior temporal gyrus.

Friedrich *Goltz* - 1881 – was the major opponent of localizationism of his time; he postulated that brain works as a whole. He claimed that Hitzig’s results were behaviorally irrelevant since the total paralysis one would expect from ablation of a real motor control center never occurred.

During the 1st half of 20th century, several influential neuroscientists continued to advocate globalism. Karl *Lashley* was most important. He proposed two principles of brain function:
a) *mass action*: the brain works as a single system
b) *equipotentiality*: all parts have equal ability to perform different tasks

He based his ideas on a long series of experiments to try to find the locus of learning by studying maze learning in rats with various brain lesions. He declared that brain function is widely distributed because he couldn't find such a locus. He concluded that only the extent of damage was important, not the location. However, maze learning involves many complex motor & sensory capabilities. Even when deprived of 1 capability, animals learn with another.

Other studies, notably those using electrical stimulation of exposed cortex in awake patients by Wilder *Penfield* & colleagues, continued to provide evidence of localization.

## Seeds of resolution: The distributed view

Three individuals (a neurologist, a neuropsychiatrist, and a psychologist) are important for contributing to the distributed view of brain function that is important for having led to the modern network paradigm.

1) John Hughlings *Jackson* was an English neurologist who contributed to neurology and psychology from 1861 to 1909. He developed a theory of evolutionary neuropsychology, in which 3 evolutionary levels are found in the nervous system. Functions are distributed at each level, and across the 3 levels.

Jackson proposed that cortical lesions cause “negative” symptoms (as well as positive ones), in which the loss of cortical control releases the same function at a lower level. He gave the example of a brain-injured patient who could not voluntarily speak, but could emit speech involuntarily, i.e. even though he could not find the word for a simple object, he could still swear vigorously when provoked. Thus, Jackson argued against a strict localizationist view of brain function.

2) *Wernicke* (1874) also proposed the idea that complex functions (e.g., language) are composed of localizable simple perceptual and motor functions:

a) complex functions are composed of separate components -- proposed that language is not a single function, but has at least 2 components (i.e. comprehension and articulation).

b) functions localized in distinct brain areas are not complex attributes as postulated by phrenologists, but are much simpler perceptual and motor functions.

3) The idea of a distinction between complex and elementary functions was supported by Lev *Vygotskii* (1934), a Russian psychologist who emphasized the developmental nature of complex psychological functions. They are not elementary and indivisible, but rather they may change their composition from one stage of development to the next.

## Summary of distributed view

The distributed view was clearly articulated by Alexander *Luria* (1975): "The higher forms of human psychological activity and all human behavioral acts take place with participation of all parts and levels of the brain, each of which makes its own specific contribution to the work of the functional system as a whole."

1) Elementary functions are localized, but the brain works in a distributed manner to produce complex functions that are not localized.

Why are elementary functions localized to particular brain areas?
Because neurons that perform an elementary function:
a) receive from the same input sources
b) project to the same output targets
c) must interact quickly

2) Complex functions are carried out by distributed combinations of simple functions. The simple functions are localized in many different places in the brain. They can be carried out by different elementary functions at different times, allowing them to be performed in different ways. Thus, different "strategies" can be implemented as different combinations of simple functions.

**Resolving elements of localizationism and globalism, the distributed view has evolved into the modern network paradigm in neuropsychology.**

## The concept of “neural network” in artificial intelligence

To understand the network paradigm also requires examining the history of the concept of “neural network” outside of neuropsychology.

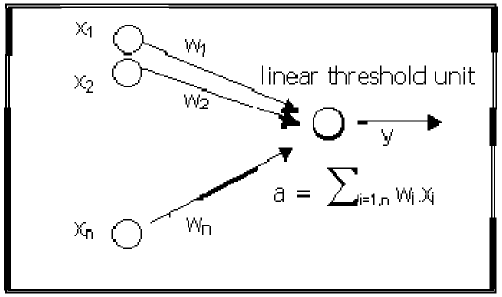
The modern history of artificial intelligence can be traced back to the 1940's, when 2 complementary approaches to the field originated.

The *Serial Symbol Processing* (SSP) approach began in the 1940's, when the architecture of the modern digital computer was designed by John v*on Neumann* and others. They were heavily influenced by the work of Alan *Turing* on finite computing machines. The *Turing Machine* is a list of instructions for carrying out a logical operation.

The *von Neumann computer* follows this theme. It:
a) performs one operation at a time
b) operates by an explicit set of instructions
c) distinguishes explicitly between stored information & the operations that manipulate information.

The *Parallel Distributed Processing* (PDP) approach (also called *connectionism*) may also be traced to the 1940's.

In 1943, Warren *McCulloch* and Walter *Pitts* proposed a simple model of the neuron – the *linear threshold unit*. The model neuron computes a weighted sum of its inputs from other units, and outputs a one or zero according to whether this sum is above or below a threshold.




*McCulloch* & *Pitts* proved that an assembly of such neurons is capable in principle of *universal computation*, if the weights are chosen suitably. This means that such an assembly could in principle perform any computation that an ordinary digital computer can.

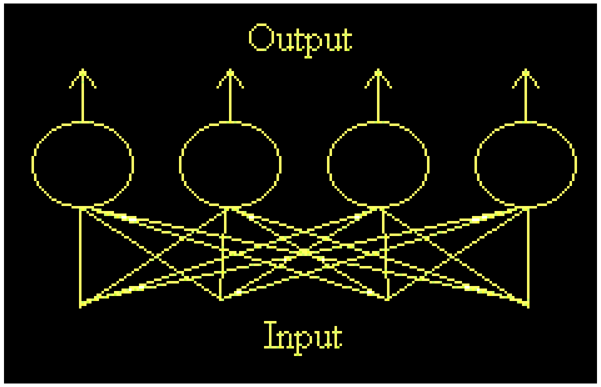
In 1949, Donald *Hebb* constructed a theoretical framework for the representation of short-term & long-term memory in nervous system.

The functional unit in Hebb's theory is the *Neuronal Assembly*:  a population of mutually excitatory neurons that when excited together becomes functionally linked.

He also introduced the *Hebbian learning rule*: when unit A and unit B are simultaneously excited, the strength of the connection between them is increased.

A leading proponent of the PDP approach was Frank *Rosenblatt*.

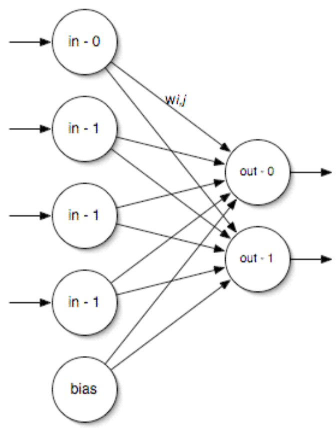
In the late 1950's, he developed the concept of the *perceptron*: a single-layer network of linear threshold units without feedback.



The work focused on the problem of determining appropriate weights for particular computational tasks. For the single-layer perceptron, Rosenblatt developed a *learning algorithm* – a method for changing the weights iteratively so that a desired computation was performed. (Remember that McCulloch & Pitts had proposed that the weights in their logic circuits had to be appropriate for the computation.)

The properties of perceptrons were carefully analyzed by *Minsky* & Papert in their 1969 book "Perceptrons". They showed that Rosenblatt’s single-layer perceptron could not perform some elementary computations. The simplest example was the “exclusive or” problem (the output unit turns on if 1 or the other of 2 input lines is on, but not when neither or both are on).

Rosenblatt believed that multi-layer structures could overcome the limitations of the simple perceptrons, but he never discovered a learning algorithm for determining the way to arrive at the weights necessary to implement a given calculation.




Minsky & Papert's analysis of the limitations of one-layer networks suggested to many in the fields of artificial intelligence and cognitive psychology that perceptron-like computational devices were not useful. This put a damper on the PDP approach, and the late 1960's and most of the 1970's were dominated by the SSP approach & the von Neumann computer.

During this time, many grandiose claims for the SSP approach were not fulfilled. Also, the backward propagation of error technique was discovered.
These developments led to a resurgence of interest in PDP models in the late 1970's.

It was realized that, although Minsky & Papert were exactly correct in their analysis of the one-layer perceptron, their analysis did not extend to multi-layer networks or to systems with feedback loops.

The PDP approach has gained a wide following since the early 1980's.
Many neuroscientists believe that it embodies principles that are more neurally realistic than the SSP approach. Because PDP models are thought to work like brain regions, they are often called *artificial neural networks*.

## Properties of artificial neural networks

1) Artificial neural networks (ANNs) are organized as layers of units.
2) A *feedforward network* has an input layer, an output layer, and one or more hidden layers.
3) Each unit has an *output,* which is its activity level, and a *threshold,* which is a level that must be exceeded by the sum of its inputs for the unit to give an output.
4) Connections between units can be excitatory or inhibitory. Each connection has a *weight,* which measures the strength of the influence of 1 unit on another.
5) Neural networks are *trained* by teaching them to produce certain output when given certain input.

*Example: training by backward error propagation*:
(1) randomize the weights
(2) present an input pattern
(3) compare the output with the desired output (i.e. compute the error)
(4) slightly adjust the weights to reduce the error
(5) repeat (2) - (4)

6) The trained network functions as an *associative memory*: it relates patterns from the input space to corresponding patterns in the output space.

7) The network can also be considered to perform a *mapping* of input space to output space.

8) The pattern of weights on the internal connections of the network can be considered to be a *representation*: they represent the combinations of input features that identify output patterns.

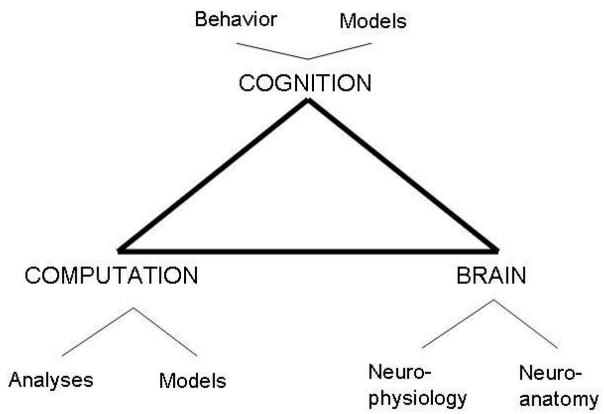
9) A *recurrent network* has excitatory or inhibitory feedback connections from higher units back to lower units that modulate their processing.

## Essentials of the network paradigm in cognitive neuroscience

The modern study of neural networks in cognitive neuroscience operates according to several fundamental assumptions that are based on the historical developments in neuropsychology and artificial intelligence that we have outlined:

1) cognitive information is represented in widely overlapping and interconnected networks of neurons in the cerebral cortex.
2) cognitive functions consist of functional interactions within and between cortical networks.
3) cortical networks develop on a core of organized modules of elementary sensory and motor networks, to which they remain connected.
4) the cognitive code is a relational code, based on *connectivity* between discrete neuronal assemblies of the cortex; any neural element of cognition derives its meaning from its contextual relations to others.
5) the cognitive code has enormous diversity and specificity, which derive from the myriad of possible combinations in which neuronal assemblies may interact.
6) a cortical neuron may be part of many different networks, and thus may participate in many percepts, memories, etc.
7) a cortical network may participate in more than one cognitive functions.

# Methods in cognitive neuroscience




Remember the cognitive neuroscience triangle. We can use it to identify the main types of technique used in cognitive neuroscience use to study the relation between brain function and cognition.

1. Behavioral Analysis
2. Neurophysiology
3. Neuroanatomy
4. Computational Analysis
5. Computational Modeling (Cognitive & Neural)
6. Perturbation Methods

1. Behavioral Analysis

a. Types

Verbal (e.g. naming an object)
Nonverbal (e.g., pressing a button)

b. Measurement

Behavioral analysis often involves measuring the *response time* (delay after a stimulus) and/or *accuracy* (fraction of correct responses)

c. Applications

*Task analysis* examines the behavior of subjects engaged in experimental tasks

*Lesion analysis* examines the behavioral consequences of accidental or therapeutic brain lesions in humans and experimental brain lesions in animals

d. Tests

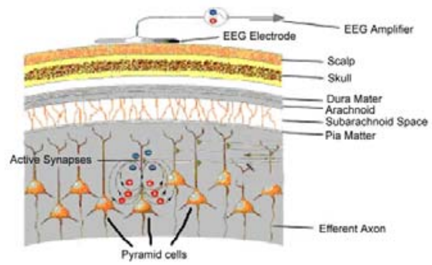
Delayed matching tasks
Stroop Test
Wisconsin Card Sorting Task (WCST)
Sternberg Paradigm

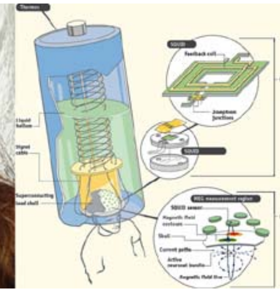
## 2. Neurophysiology

a. Neuron (unit) activity
*Single-unit*: spike trains from single isolated neurons in the brain
*Multi-unit*: spike trains from multiple neurons in the brain

b. Population (field potential or field) activity
*Electroencephalogram (EEG)*: recording of cortical electrical activity from extracranial sensors
*Magnetoencephalogram (MEG)*: recording of cortical magnetic activity from extracranial sensors
*Local Field Potential (LFP)*: recording of cortical electrical activity from microelectrodes in cortex
*Intracranial EEG (iEEG)*: recording of cortical electrical activity from macroelectrodes in cortex
*Electrocorticogram (ECoG)*: recording of cortical electrical activity from macroelectrodes on surface of cortex

The Event-Related Potential (ERP) is derived from the EEG, LFP, iEEG, or ECoG by a 2-step process: (1) alignment of multiple time traces to a common sensory, cognitive, or motor event; (2) averaging the traces at each time point. The ERF is produces from the MEG by the same process.

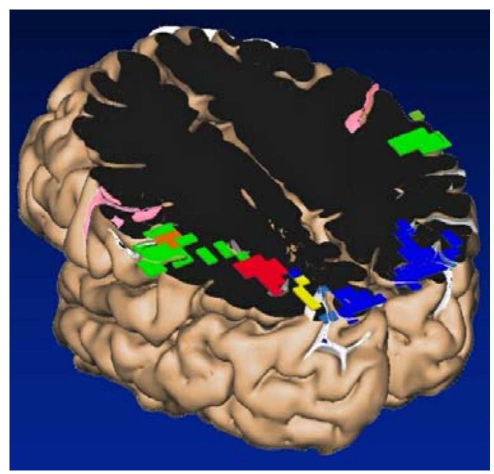


c. Functional brain imaging

*Positron Emission Tomography (PET)*: tomographic imaging of brain activity from emitted gamma rays from radioactive tracers

*Functional Magnetic Resonance Imaging (fMRI)*: tomographic imaging of brain activity from the Blood Oxygen Level (BOLD) signal

The use of PET and fMRI in cognitive neuroscience is based on the concept that the neurons in brain regions which are involved in a cognitive function increase their metabolic activity during that function.

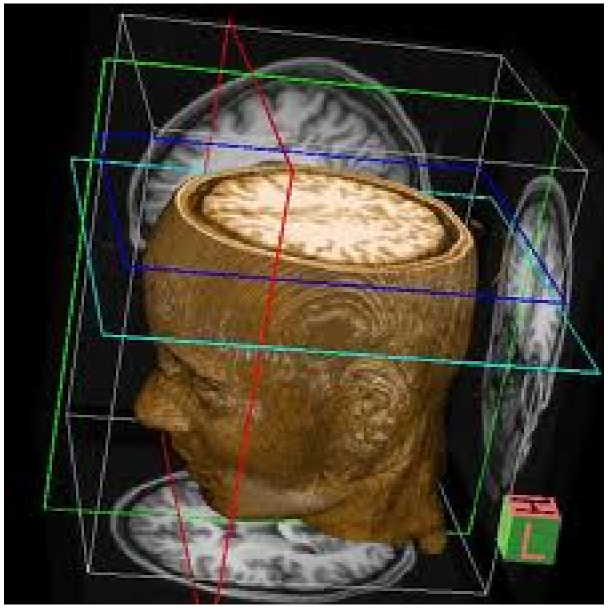
Ex 1: in FDG PET imaging, a radioactively labeled glucose analog is injected into the bloodstream, is taken up into the brain, and then in higher amounts in metabolically active cortical neurons.

Ex 2: in fMRI BOLD imaging, the ratio of oxygenated to un-oxygenated hemoglobin in the red blood cells of the local microcirculation is lower in metabolically active cortical regions.

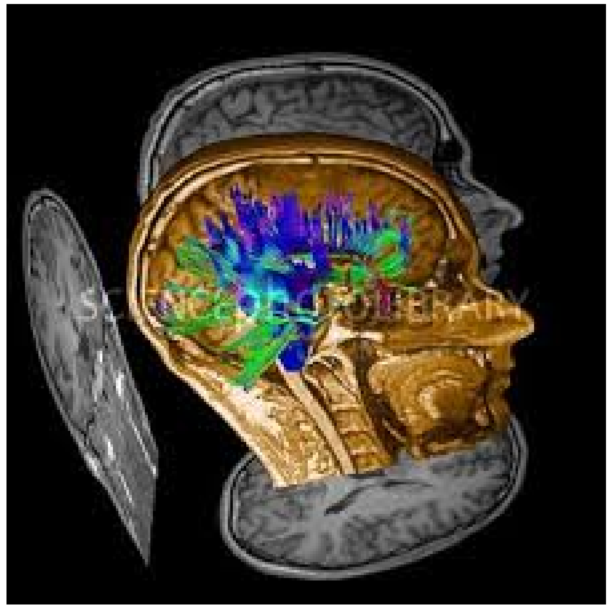
3. Neuroanatomy

a. *X-ray Computed Tomography (CT)*: 2D and 3D images of the brain are constructed by tomography from differences in x-ray absorption

b. *Structural Magnetic Resonance Imaging (sMRI)*: 2D and 3D images of the brain are constructed by tomography from differences in the radio frequency signal of excited hydrogen atoms as they return to their equilibrium states



c. *Tractography*: 3D modeling techniques that image brain pathways (tracts) using *diffusion tensor imaging (DTI)* or *diffusion spectrum imaging (DSI)*, two variants of magnetic resonance imaging. Diffusion imaging maps the diffusion of water molecules in the brain.



4. Computational Analysis

a. Logical analysis

Determination of the computational (information processing) steps necessary to perform a cognitive process

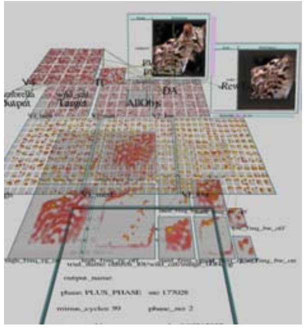
b. Simulations

Artificial generation of imitations (or reproductions) of cognitive processes, usually in a digital computer but also in other hardware such as robots

# 5. Computational Modeling

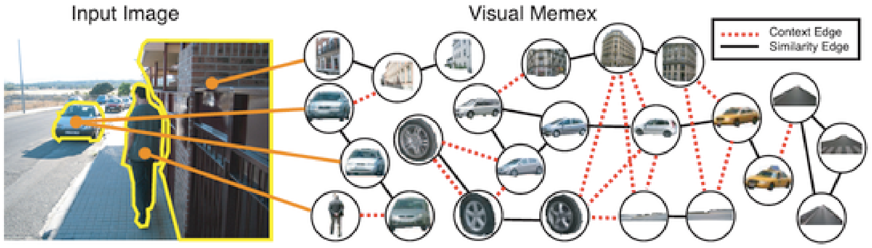
## a. Artificial Neural Network Models (PDP approach)

Models of cognitive processes constructed from ANNs having simple non-algorithmic function



## b. Symbolic Models (SSP approach)

Models of cognitive processes constructed from symbolic elements having algorithmic function



## 6. Perturbation Methods

### a. Pharmacology

Pharmacological perturbation is a technique that involves administration of chemical agents that affect brain function

### b. Electrical Brain Stimulation

Electrical stimulation of brain regions or pathways with indwelling electrodes

### c. Transcranial Magnetic Stimulation (TMS)

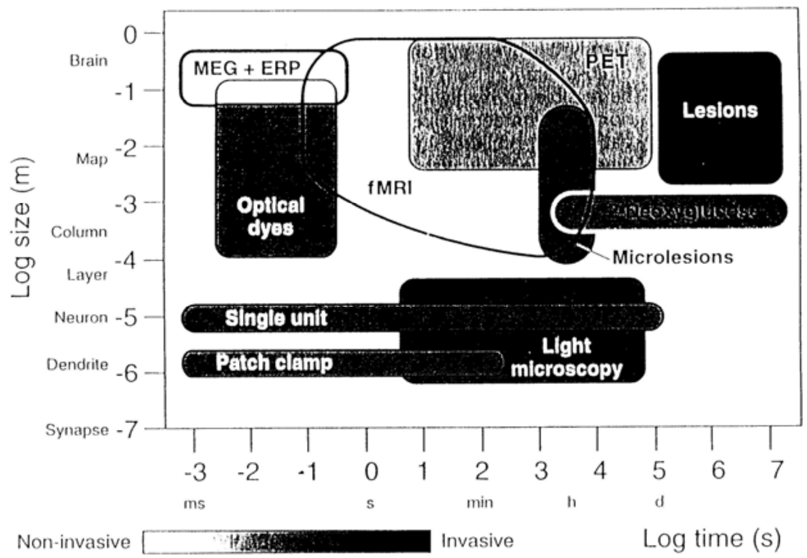
A noninvasive technique for stimulating focal brain regions in healthy humans. It can be used either to activate a region or to produce a “virtual lesion” by disrupting ongoing activity.

### d. Transcranial Direct Current Stimulation (tDCS)

A noninvasive technique similar to TMS that uses electrical rather than magnetic stimulation.

Both TMS and tDCS are used in conjunction with sMRI to localize the target region

# Temporal scale, spatial scale, invasiveness




EEG, MEG, and fMRI are the 3 techniques currently most used to study cognitive neuroscience in humans. The first 2 have good temporal resolution but poor spatial resolution. The 3$^{rd}$ has good spatial resolution but poor temporal resolution. All 3 are non-invasive.

Unit activity is the technique currently most used to study cognitive neuroscience in experimental animals. It has good temporal resolution but poor spatial coverage. It is invasive.