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*.

A matter of correlation

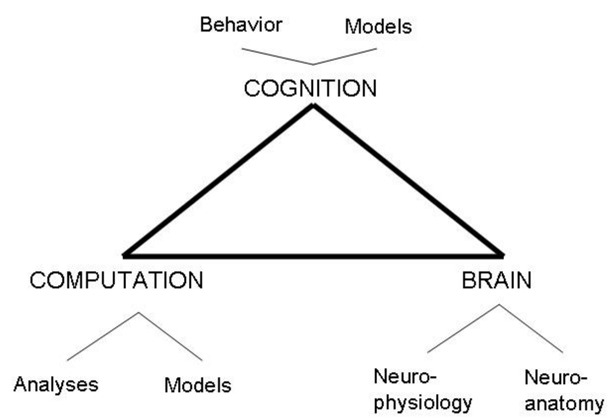
We take a functionalist approach to the study of cognitive neuroscience. This reduces the mind-brain problem to the computational mind-brain problem. But we are still left with the problem that theories of the computational mind in cognitive science and theories of the brain in neuroscience represent two *independent systems of description*. Cognitive neuroscience has not developed to the point where it has established causal relations between cognitive 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.

Most of the work in this field aims to determine:
1) the neural structures that carry out cognitive functions, and
2) the neural mechanisms by which the structures carry out the cognitive functions.

The cognitive neuroscience triangle (Kosslyn & Koenig 1992)

This concept is useful in the study of cognitive neuroscience. 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)



Emergence of the distributed paradigm in neuropsychology

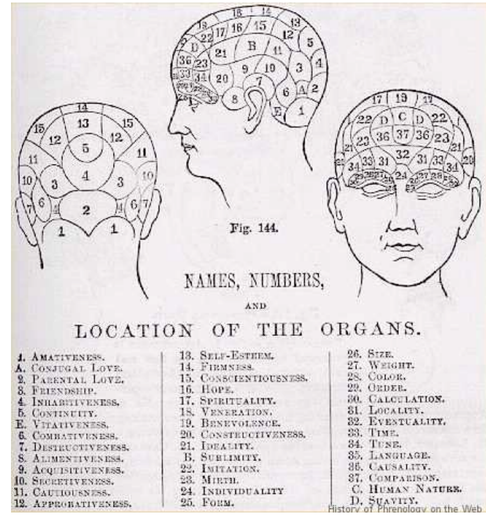
To understand the difference between the modular and network paradigms, it is necessary to examine the history of understanding the relation between brain function and cognition. This history has been dominated by two parallel trends: *localizationism* and *globalism*, and has led to the emergence of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

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.

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 continues in the 19th and 20th centuries

Some clinical evidence suggested localization of function:

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. Knowing of Broca's work, he also distinguished elementary from complex function in language.

Friedrich *Goltz* - 1881 – was the major opponent of localizationism of his time; he postulated that brain works as a whole.

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.

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

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.

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 cognitive neuroscience.

The concept of “neural network” in cognitive neuroscience

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.

The concept of “neural network” in computational cognitive neuroscience

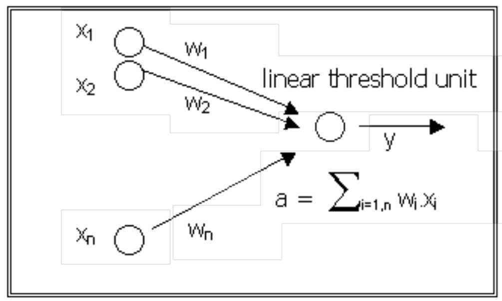
To understand the computational aspects of the network paradigm requires examining the history of the concept of “neural network” in the field of artificial intelligence. The modern history of artificial intelligence can be traced back to the 1940's, when 2 complementary approaches to the field originated.

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.



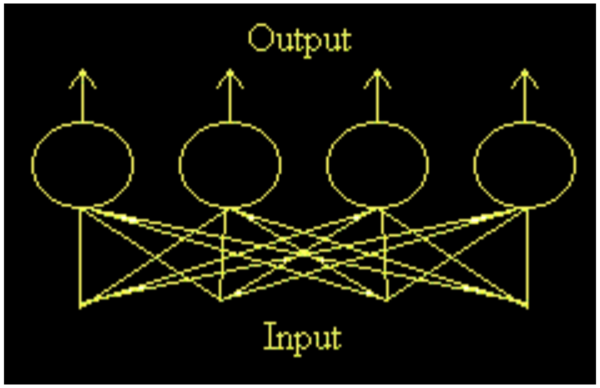
McCulloch & *Pitts* proved that an assembly of such neurons is capable in principle of *universal computation*, if the weights are chosen suitably. This means that such an assembly could in principle perform any computation that an ordinary digital computer can.

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.

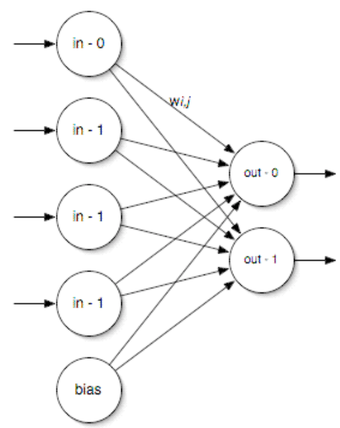
Hebb also introduced the *Hebbian learning rule*: when unit A and unit B are simultaneously excited, the strength of the connection between them is increased.

The *perceptron*, a single-layer network of linear threshold units, was developed by *Rosenblatt* in the late 1950's.



Rosenblatt developed a *learning algorithm* – a method for changing the weights in the perceptron 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.) Rosenblatt believed that multi-layer structures could overcome the limitations of the single-layer network.

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*.



Recent interest in artificial neural networks has focused on *deep learning*, with applications in many fields, such as computer vision, speech recognition, natural language processing, social network filtering, machine translation, and drug design, and with results that are in some cases superior to human experts.