Intelligence is the most difficult cognitive function to define. It is manifested in many different ways.

Fuster defines it as “the ability to adjust by reasoning to new changes, to solve new problems, and to create valued new forms of action and expression.”

This definition approaches what it means to display intelligent behavior, but it is not completely adequate.

Another approach is simply to list some common cognitive abilities that contribute to intelligence:
  1) reasoning
  2) problem solving
  3) decision making
  4) creativity

These abilities are discussed in chapter 8, in light of the question, “what are there cortical correlates of intelligence?”
Development of Intelligence

Intelligence is seen through behavior, but all behavior is not intelligent.

Animals are capable of intelligent behavior. E.g. a monkey performing a delayed match to sample task is involved in problem solving, an ability of intelligence.

Even though humans are not the only intelligent living beings, human intelligence represents a “quantum leap” in the evolution of cognition.

Humans have a number of cognitive abilities of which all other species are incapable.
These include:
1) language
2) abstract thought
3) sophisticated tool manufacture & use
Intelligent behavior is supported by other cognitive functions, such as attention and memory.

The development of human intelligence depends on the development of adaptive behavior. Adaptation to the world involves reasoning directed to the pursuit of goals.

The development of intelligence therefore depends on development of cortical cognitive networks.

It also depends on development of efficient information processing in cortical cognitive networks.

The efficiency of that information processing may underlie varying degrees of intelligence.

Efficiency may be defined as “the ability to use available means, including prior knowledge, to attain a goal such as the solution of a problem”.

Intelligence tests commonly emphasize *efficiency of performance*.
It is believed that animals become progressively more efficient at information processing in evolution. It can be said that evolution has brought about a progressive increase in intelligence of species (increased efficiency in the functioning of cognitive abilities).

Likewise, in early human development the individual becomes progressively more efficient at information processing with age.

**Conclusion:**
In both phylogeny and ontogeny, the development of intelligence closely correlates with cortical development, especially development of association cortex.

**Phylogeny:**
Species having a large evolutionary expansion of the cerebral cortex (primates) also show high cognitive ability.

**Ontogeny:**
The development of cognitive ability in the individual member of primate species in the “formative” years parallels maturation of the cortex, especially association cortex.
However, there are no known correlates between cortical structure, either macroscopic or microscopic, and intelligence measures. If there is a basis for intelligence in brain structure, it is not accessible by any measure currently available.

For example, the brain of Albert Einstein has been highly scrutinized with the goal of finding some structural marker that distinguishes it from the average human being. It has been reported that the brain has a higher than normal proportion of oligodendroglia, and also that the inferior parietal lobe is 15% wider than normal.

However, the reported effects are still controversial, and this is just one famous brain that has received a great deal of attention. In general, no significant correlation has been established between cortical structure and intelligence.
Jean Piaget pioneered the study of intellectual development in the child.

Piaget’s studies consisted mainly of observational field work. He did not use rigorous quantification or statistical testing.

Piaget’s theory of child intellect development consists of 4 distinct stages, each within a well-defined age range.

1. *sensory-motor stage* (birth – 2 years)
   a. the child learns to integrate complex sensations and movements, extending the basic (simpler) reflexes present at birth.
   b. the child begins to develop schemata of sensory-motor integration (characterized by stereotypical pantomimes).

2. *representational stage* (2 – 7 years)
   a. the child extends the use of symbolism to the verbal domain to represent the world.
   b. the child develops the ability to manipulate objects, which becomes progressively more regulated by *feedback from the environment*, and refined by *trial and error*.
   c. as language comprehension develops, this feedback includes progressively more language from other people.
3. **concrete operations stage** (7 – 11 years)
   a. the child becomes less stimulus-bound, and more independent in being able to organize behavior (including use of language) to achieve goals.
   b. there is a great increase in improvisation and creativity.

4. **formal operations stage** (11 – 15 years)
   a. the child begins to use hypothetical reasoning and problem-solving abilities.
   b. inductive and deductive logical skills develop.
   c. the capability for purposive behavior develops along with the ability to construct temporal gestalts of logical thought and action to achieve distant goals.
   d. language is well-integrated in goal-directed behavior as the formulation of propositions in the construction of goal-directed gestalts.
Piaget’s approach is valuable, and his methodology is useful, but it is “insufficient cognitively and neurobiologically”.

Later work has provided necessary qualifications.

Some criticisms of Piaget’s theory:
  1. the stages are too rigid in their boundaries: different children transition between stages at different times.
  2. it lacks the exclusionary aspect of attention in behavior: the child must develop the ability to suppress distracting sensory inputs, alternate constructs, conceptually competing categorizations, etc.
  3. children can reason with numbers at an earlier age than he proposed.
Some important contributions of Piaget’s theory:

1. Piaget’s scenario of stages properly emphasizes the increasingly higher levels of integration (formation of high-level associations) that occur in childhood intelligence development.

2. In transitioning from one stage of development to another, cognits at progressively higher levels take over integrative functions that were supported by lower-level cognits in earlier stages; in this process, lower levels may be subordinated rather than suppressed.

3. The perception-action cycle (PAC) is involved in this developmental process: it provides integration of posterior sensory and frontal executive motor areas at different hierarchical levels, and progressively higher levels of integration may occur with successive stages of intelligence development.
The onset of participation of a hierarchical level in the PAC at a particular stage of development may depend on the *structural maturation* of the areas at that level.

**Example 1:** the use of verbal symbolism in the *representational stage* may depend on maturation of association areas supporting symbolic cognits.

**Example 2:** the high-level cognitive abilities of the *formal operations stage* may depend on maturation of the prefrontal cortex, which is latest to mature.

Functions that depend on interactions at the top of the PAC require prefrontal control, and thus depend on prefrontal maturation:
1) intricate behavioral sequences
2) logical constructs
3) elaborate sentences
Anatomy of Intelligence

A distinction must be made between the structural and functional anatomy of intelligence.

Structural anatomy

This refers to the cortical “fund of knowledge” upon which intellectual activities depend.

This knowledge base varies across individuals.

The information storage capacity of the cortex is essentially unlimited in the normal adult. It is only limited by severe mental retardation, extensive cortical malformation, disease, or trauma. Therefore, structural anatomy does not, in principal, limit intelligence.

Functional anatomy

This refers to the cognits that process knowledge in the service of intellectual activities.

The specific cognits involved vary with the intellectual activity being performed.
The structural and functional anatomies overlap because the cognits that process knowledge for intelligent behavior use the cognits that store that knowledge, and may be the same.

The cognits involved and the degree of overlap depend on the specific type of information being processed.

To consider the neural dynamics of intelligence requires that the different forms of intelligent performance first be delineated. For this, we consider Sternberg’s classification.
Sternberg classification of intelligence

1) *analytical intelligence*: based on reasoning
2) *practical intelligence*: based on problem-solving abilities acquired mostly by ordinary life experience
3) *creative intelligence*: based on conceiving, imagination, intuition

Individuals vary as to their use and command of these 3 types of intelligence. Therefore, it is considered useful to have a measure that quantifies intelligence. This goal has led to the development of intelligence tests.
Intelligence tests

In 1905, Binet developed a test for intelligence to be given to French school-children.

Many other similar tests have been developed since then. Most rate intelligence in reference to standardized scales of a person’s mental age.

Mental age is combined with chronological age to derive an Intelligence Quotient (IQ).

The most common tests used in the US are:
1) Stanford-Binet
2) Wechsler-Bellvue
   a. Wechsler Intelligence Scale for Children (WISC)
   b. Wechsler Adult Intelligence Scale (WAIS)
Most measures of intellectual ability tend to correlate with one another. This has led to attempts to derive a measure of *general intelligence*.

The *Spearman g-factor* was derived for this purpose.

*Raven’s Progressive Matrices (RPM)* test is a test of “fluid” intelligence that has been used in many studies of analytic intelligence; it can be used to derive the Spearman g-factor.

*Fluid intelligence* refers to the performance of tasks that require manipulation of novel information; it is typically non-verbal.

*Crystallized intelligence* refers to tasks performed by retrieval of existing knowledge from long-term memory; it is commonly verbal.

Since attention “ensures the selective allocation of cognits to the processing of information in new situations, as in the solution of new problems”, it is highly correlated with intelligence.

Both attention and intelligence rely heavily on prefrontal executive networks.
Electrocortical studies of intelligence

Many studies have tried to find an electrocortical correlate of intellectual performance.

It has been shown that a relation exists between IQ and the EEG:
1) a relation has been reported between IQ and EEG frequencies in high alpha/low beta range.
2) it has been reported that coherence in the theta range between frontal and posterior cortices is a reliable correlate of intelligence. This finding suggests that intelligence depends on reentrant processing between these areas.
Neuroimaging studies of intelligence

There is abundant evidence for prefrontal network involvement in intellectual performance.

Many tasks show activation of the anterior cingulate cortex (ACC) as well as the lateral prefrontal cortex.

Duncan (1996) proposed that general intelligence, as measured by the Spearman g-factor, depends on the prefrontal cortex.

The Spearman g-factor is lowered by prefrontal lesion and is elevated in normal subjects by tasks that activate prefrontal cortex.

A 2000 study by Duncan recorded PET in subjects performing problem-solving tasks high in Spearman g-factor.

The results (Fig. 8.2) show that those tasks activate lateral prefrontal cortex.

The tasks may also have involved a variety of perceptual cognits in widely distributed posterior cortical areas.
Reasoning

Reasoning is logical thought, including both deductive and inductive logic. It includes mathematical as well as linguistic operations. It may be unconscious as well as conscious.

From a phenomenological perspective, reasoning may be defined as the formation of new knowledge from prior knowledge.

In terms of cortical cognitive networks, reasoning is the formation of new cognits from existing ones.

A new cognit that is formed from existing ones may be considered to be an *inference*.

An inference may be based on:
1) pre-existing knowledge
2) new sensory information
3) recent sensory information
2 main methodologies in the cognitive science of reasoning:

1. Linguistic (SSP): predicated on rule-based symbolic formalization of knowledge.
   Linguistic reasoning is propositional.

   Connectionist reasoning is nonpropositional.

The human brain used both linguistic and connectionist forms of reasoning, and both probably rely on interaction of lexical and cognitive networks. However, the brain mechanisms of reasoning are unknown.

Many different cognitive models of reasoning have been proposed. The models vary in their degree of neural plausibility, depending on how much they take into account known cortical anatomy and physiology, and dysfunction.
Symbolic reasoning models typically are based on an executive processing unit (agent).

The agent plans the successive rule-based processing stages of words and propositions.

Representations are intelligible at every stage.

Connectionist reasoning models are not based on rules and do not have a central executive. Knowledge is distributed throughout the network. Reasoning occurs in parallel operations of network units. Knowledge exists in the connections between units that are formed by learning.

Representations are generally unintelligible at all stages.
Reflexive reasoning refers to rapid, automatic inference formation drawn from a large knowledge store.

It is usually unconscious and intuitive.

An attempt at modeling reflexive reasoning is the Shastri connectionist model:

It has a connectionist architecture with a large body of facts “encoded” in its patterns of connectivity.

A set of elementary inference rules is also encoded in connectivity patterns.

The interplay of facts and inference rules gives the system a rudimentary ability for deductive reasoning – the model quickly (< second) generates inferences based on incoming “sensory” patterns.

The model represents an item of knowledge as a synchronous rhythmic activity pattern (dynamic binding). Reasoning occurs as the transient propagation of these patterns through the system. It depends on a rapid matching process that compares sensory patterns to internal patterns representing facts in the network.

The rapid matching process is based on contingency rules embedded in the system.
The degree of neural plausibility of this model is unknown.

However, the Shastri model is generally consistent with cognit theory:
1. matching of sensory input to internal knowledge structures
2. representation of objects, facts, propositions by prior association
3. activation of representations by binding (selective activation of associated network elements)

The Shastri model is inconsistent with cognit theory in:
1. In the model, information is represented by temporal activity patterns
2. In cognit theory, information is represented by spatial activity patterns

In general, computational models of cognitive function are neurobiologically implausible because:
1) the models lack biophysical detail.
2) they are based on assumptions based on questionable interpretation of neural data.
Johnson-Laird (1995) proposed that deductive reasoning (“top-down” logic linking premises and conclusions) consists of the construction of nonverbal, nonpropositional “mental models” of reality.

Multiple alternative models, and their potential consequences, are tested against reality.

One implication of this view is that model construction and testing takes place in nonverbal processing areas of cortex. This view is supported by evidence that right-hemisphere lesions impair nonverbal aspects of reasoning.

However, some functional imaging studies suggest that deductive reasoning depends on language areas of the left hemisphere. The results of some lesion studies also agree that the left hemisphere supports deductive reasoning.
The PET study of Goel et al. (1998) had subjects perform 3 different kinds of deductive reasoning (syllogism, spatial relational inference, nonspatial relational inference). (Examples of propositions presented to the subjects are shown in Table 8.1). Control tasks required judgments about the semantic content of the sentences without judgment based on logic.

The differences between task and control PET images were left lateralized (Fig. 8.3). Left-hemisphere activation included inferior & middle frontal gyri, as well as temporal and anterior cingulate cortex.

The Goel et al. study suggests that:
1) left-hemisphere language areas are used for deductive reasoning
2) left-hemisphere language areas are activated in spatial reasoning
3) spatial & nonspatial deductive reasoning both use the same left-hemisphere cortical areas
4) strong activation of dorsolateral PFC likely indicates that this region is involved in the integrative processing required by deductive reasoning.

However, it is unlikely that no other cortical areas are involved in deductive reasoning. Other areas may provide weaker and/or more time-limited contributions that do not show up in neuroimaging.
Another PET study by Houdé et al. (2000) investigated the cortical basis of reasoning (about colored geometrical forms).

Subjects initially made numerous errors due to incorrect perceptual bias from misinterpreting the rule. However, through training they were able to develop a logical bias that overcame the perceptual bias and improved performance.

The PET results showed a cortical displacement of posterior activation to frontal activation with training (Fig. 8.4). This shift was interpreted as due to the suppression of the perceptual bias from posterior areas as a result of training.

The exercise of logical reasoning in the Houdé et al. study thus appears to have come from the PFC taking executive control of the task, which overcame perceptual biasing influences from the posterior cortex.
Conclusions about reflexive reasoning:
1) reflexive reasoning depends on rapid, parallel, unconscious information processing between low-level cognits.
2) such information processing involves matching of cognits to reality (perceptual input).
3) this matching automatically produces inferences.

Conclusions about deductive reasoning:
1) deductive reasoning is a high-level (at the top of the PAC) integrative process.
2) inferences are reached by sequential matching of alternative cognits against reality and permanent cognits.
3) left-hemisphere linguistic processing plays a role in the processing.
4) the processing requires lateral PFC involvement for the integration of complex information over time and the suppression of alternative conclusions.
5) suppression of inferences that are “logically nearly true” provides a strong load on the information processing capacity.
**Problem Solving**

Problem solving is a cognitive process directed at achieving a goal when a solution method is not obvious to the problem solver.

Inductive reasoning is used more than deductive reasoning for solving problems in everyday life.

Both forms of reasoning appear to share the same cortical substrate.

Deductive reasoning seeks to draw and verify logically valid inferences from premises. Validity is the logical consistency between inference and premises.

Inductive reasoning seeks to draw plausible inferences from current observations and preexisting knowledge, and to estimate the probability of those inferences. At best, induction attains high probability, not truth.

Scientific discovery depends heavily on inductive reasoning, “as natural science is a process of successive probabilistic approximations of personal knowledge to the reality of the physical world”.

Ordinary problem solving uses practical intelligence to make inductive inferences leading to the goal of a problem solution.
When the inferences derive from similarities and lead to conclusions by similarity in a cognitive process, the logic is called *analogical reasoning*.

In analogical reasoning, similar stimuli are treated as equal and the problem-solving strategy is re-used on a new similar problem.

Analogical reasoning is applied to relationships between stimuli, objects, and events, as well as to the stimuli, objects, and events themselves.

The process is similar to that proposed by Gestalt psychology for the making and recognition of percepts.

Analogical reasoning involves creation and use of *analogical mappings*, that are essentially abstract cognits, used as gestalts.

Problem solving uses neural interactions among cognits of established knowledge, as well as of current and recent sensory information, to reach the solution of a problem.

Problem solving also calls on attention, perception, memory, and the integration of conditional contingencies to reach the solution goal. The integration is temporal when multiple complex contingencies are involved.
Problem-solving tests

In general, there is no widely accepted definition of problem solving that would allow its reliable and valid measurement.

The CRESST (Center for Research on Evaluation, Standards, and Student Testing) model of problem solving includes four elements:
   1) content understanding
   2) problem-solving strategies
   3) metacognition (planning, self-monitoring)
   4) motivation (self-efficacy, effort)

In humans, the Raven’s Progressive Matrices (RPM) test (Fig. 8.5) is used to test analogical reasoning.

In nonhuman primates, problem solving is tested using cross-temporal contingency tasks, e.g., delay tasks. These tasks test temporal integration functions, such as working memory and prospective set, in problem solving.
Functional neuroimaging studies of problem solving

These studies provide understanding of the cortical topography of the cognits involved in problem solving.

Functional neuroimaging during problem solving reveals the activation of large regions of cortex, mostly in the left hemisphere but, also in the right in some cases.

Two groups of areas are consistently activated:
1) the first group is in posterior cortex: the location and extent of activation depends on the type of information used to problem solve.
2) the second group is in frontal cortex; areas involved are anterior cingulate cortex, Broca’s area, lateral PFC.

The relative timing of the activations of these 2 groups is not revealed by functional neuroimaging: they may be concurrent or sequential.

Problem solving that involves:
1) spatial reasoning (e.g., imagination of 3-D rotational transformation) activates the TPJ region (the junction of the occipital, temporal, and parietal lobes).
2) analogical reasoning (e.g., the RPM task) activates the posterior parietal cortex.
3) text processing activates Wernicke’s area.
Conclusion

Problem solving activates at least two regions:
1) one region of posterior cortex that specializes in the representation and processing of the cognitive content used to arrive at the correct solution.
2) prefrontal cortex (PFC)

The problem task is likely to activate both perceptual cognits, representing sensory and/or semantic content, and executive cognits, that carry out execution of the task in time.

In the 2000 meta-analysis of Duncan and Owen, 3 PFC regions were activated in many tasks (Fig. 8.6):
1) anterior cingulate cortex (ACC)
2) lateral PFC
3) orbitofrontal cortex (OFC)

These 3 regions appear to contribute:
1) heightened attentive effort
2) temporal integration
3) exclusionary attention: suppression of posterior cognits that interfere with the correct solution of the problem
“The integrative role of the prefrontal cortex in problem solving is graded and adjusted to need.”

3 factors determine the degree of involvement of the PFC in problem solving:
1) integration time
2) relational complexity
3) novelty

This involvement depends on the degree of “mental effort” required.

Thus, tasks that have long integration time, are highly complex, and/or are highly novel require the most effort and, hence, the highest degree of PFC involvement.
In Kroger et al. (2002), the level of PFC activation correlated with the number of relations to be integrated in a RPM analogical reasoning task.

In Waltz et al. (1999), impairment of performance on an analogical task correlated with the degree of the task’s relational complexity in PFC-lesioned patients.

In Osherson et al. (1998), more-demanding inductive reasoning problems activated left PFC to a greater degree than less-demanding problems.

An *economy of resources* in PFC (presumably related to the economy of attentive effort) is reported: problems elicit less PFC activation as they become automatic and effortless (Jahanshahi et al. 2000; Reichle et al. 2000).

Dehaene et al. (1998) speculated that the PFC regulates the contribution of its neurons to a “global workspace” used for problem solving.