

# **The Biological Basis of Thinking and Learning**

by  
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# The FOSS Program

The Full Option Science System (FOSS) is a “new generation” science program made possible through a grant from the National Science Foundation. This program was developed at the Lawrence Hall of Science at the University of California, Berkeley.

FOSS is a non-textbook program. Because research indicates that youngsters learn science best when they experience it first hand, FOSS provides classroom laboratory kits, specially designed to involve all students in explorations and experimental investigations. A teacher guide helps the teacher orchestrate each situation, integrate the activities with other subject areas, and correlate the experiences with other elementary school science resources. Student sheets are included with each FOSS activity to help the students record, organize, and analyze data.

Compared to the more frequently used textbook approach which often touches lightly on many different, unrelated topics in a school year, FOSS introduces fewer topics that are taught in greater depth. The topics are presented as instructional modules and were carefully chosen based on the following criteria:

1. Youngsters would find them interesting and worthy of in-depth exploration.
2. Each topic could be a vehicle for important, powerful, and transferable scientific concepts.

3. The topics provided opportunities for youngsters to become directly engaged in the use of scientific thinking processes: observing, communicating, comparing, organizing, relating, inferring, or applying.

4. The concepts presented were appropriate to the developmental level of the students.

The resulting modules give the program great flexibility. The modules are sufficient in content and range to be a complete, articulated program; however, the modules can also be used selectively to supplement and extend successful ongoing programs. Although schools using the program can arrange the modules to suit the purposes of the teachers and the needs of students, it is important to maintain the integrity of the FOSS modules. They should only be used for the indicated grade levels or above. Also note that modules link together vertically through the grades. Subsequent FOSS modules build on earlier ones, thereby deepening each student’s understandings of scientific concepts.

A significant component of the FOSS program is its application of current research about how youngsters think and learn. Activities within the program are designed specifically to match the cognitive capacities of youngsters, and the sequence of modules is articulated to match the cognitive growth of students over time. Suggestions to the teacher offer ways by which students can be encouraged to generate their own questions, find ways to gather data, and build bodies of evidence that support what they find out.

FOSS K-6 Program						
GRADE LEVEL	Life Science	Physical Science	Earth Science	Scientific Reasoning and Technology	THINKING PROCESSES	
Grades 5 and 6	Food and Nutrition	Levers and Pulleys	Solar Energy	Models and Designs	<b>Relating</b> Organizing Comparing Communicating Observing	
	Environments	Mixtures and Solutions	Landforms	Variables		
Grades 3 and 4	Human Body	Magnetism and Electricity	Water	Ideas and Inventions	<b>Advanced Organizing</b> Comparing Communicating Observing	
	Structures of Life	Physics of Sound	Earth Materials	Measurement		
Grades 1 and 2	New Plants	Solids and Liquids	Air and Weather		<b>Beginning Organizing</b> Comparing Communicating Observing	
	Insects	Balance and Motion	Pebbles, Sand, and Silt			
Kindergarten	Life Science		Physical Science			<b>Comparing</b> Communicating Observing
	Trees	Animals Two by Two	Wood	Paper	Fabric	

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## Foreword

Humans, for the most part, are pattern seekers. Sometimes they are playful pattern seekers as when they doodle, work puzzles, or day dream. And sometimes they are purposeful pattern seekers as when they try to get answers to things, plan ahead, or resolve problems. As humans use their pattern seeking capabilities, they come to learn about and understand their surroundings.

Today much of our world is best understood through the sciences. It is natural that this is the case because nature has prepared us to seek patterns in what we see and do, and the patterns we discover enable us to cope with, understand, appreciate, and predict events in our environment. The scientist, whether she is a biologist, physicist, astronomer, or whatever, is simply a well-practiced pattern seeker. All of us by nature are pattern seekers.

Well-tested research-based programs are designed to prepare children for the scientifically and mathematically complex societies of the 21st century. Such programs are based upon sound, current scientific knowledge about how the brain functions, how humans think and learn, and how this knowledge relates to understandings about our world.

*This monograph summarizes that research for educators.* First, it explains some of the discoveries science has made about the brain over the last ten years, due in large part to advances in medical technology. Second, it summarizes seven biologically based stages of pattern seeking capabilities that each of us—according to extensive research studies—went through from infancy to adulthood.

The FOSS Program makes use of this research knowledge to properly sequence curriculum experiences and plan learning activities so that children grasp new concepts easily. Each developmental stage is highlighted with examples of what learners do and what they enjoy learning. Although the relationship of these seven stages to learning is important in all subject areas, most examples presented here are for the content areas of the sciences.

## The Brain and Thinking

Aside from ourselves, we know of no other organism that can contemplate the outer edges of the universe or the inner workings of the atom. No other creature can imagine the future or reconstruct the past beyond the limits of its own life. How have humans, alone, been able to attain such thinking abilities? What do we, as educators, know about how humans reason? And what is important about that reasoning that must be considered as we look to the future of schooling?

Most people act as though thinking and the brain are synonymous. A fine thinker is often referred to as “brainy.” When people say, “Brains over brawn,” they clearly equate the brain to clever thinking. A “brainless” person is one who lacks intelligence. But in spite of such terminology, the brain and thinking are not synonymous. They are quite distinct.

The brain is a physical organ which, at birth, is estimated to contain about 100 billion cells. At birth it is about one-third of its eventual mass. Within two years after birth it will double in size, and over the next 15 years many of its cells will develop up to 600,000 connections between themselves and other cells (Maranto, 1984). In the past 10 years we have learned much about the physiology of the brain—its electroconductivity, chemistry, and anatomy.

Thinking, however, is the ghost in the machinery. It is something beyond the physiological attributes. Imagine looking at a chess board at midgame. The physical placements of the pieces can be described, but where are the strategies of offense and defense? Similarly, imagine touring a school and locating the rooms where the teacher and students are. Can you point to the “education” that takes place there? Thinking is to the brain as time is to a watch. The watch has hands and numerals, but where is the time? Time in a watch, strategies in a game, and education in a classroom are processes within physical configurations. And so, too, is thinking within the brain. Neurobiologists may identify one or more factors actively engaged among cells during a thought process, but with the more than 100 billion

interactions that are possible within our heads, it is the process of thinking that is of prime importance, not the physiological components.

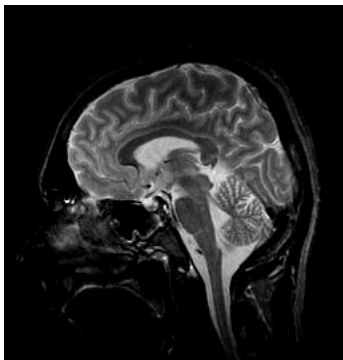
In the past 10 years, neurobiologists have made significant breakthroughs in seeing what goes on within the brain as it processes information. They are discovering what parts of our brains are used for what kinds of thought through inventive techniques that provide instantaneous, well-localized signals of brain activity. Each technique provides a different view of the brain's processes.

The EEG (electroencephalogram) and MEG (magnetoencephalography) were the earliest techniques developed for observing brain function. They record the brain's electrical impulses while they are happening.

The EEG produces an image of the brain on a computer screen. An electrode-studded cap is placed on the head of a subject, and the researcher connects a cable from the cap to a computer. The computer records localized brain activity as the subject carries out tasks.

The MRI (magnetic resonance imaging) provides detailed views of brain structures.

#### **MRI Brain Scans (side and top views)**



#### **MRI "Open" Scanner**



Recently, EEG and MEG techniques were combined with the MRI technique to construct a computer-generated, three-dimensional picture of the brain from a set of two-dimensional magnetic resonance images. The program is able to describe precisely the boundaries of each cortical area of the brain. This non-invasive technique is called functional magnetic resonance imaging (fMRI).

PET (positron emission tomography) is a brain scan that measures blood flow in the brain. Increased blood flow indicates increased metabolic activity. Such scans are used to identify which areas of the brain carry out particular tasks.

Much of the following information is based upon findings from studies that have used these techniques.

#### **Early Brain Development**

Soon after conception, brain cells begin to divide and redivide at an astonishing rate. Beginning with just a few cells at the tip of the embryo, as many as 250,000 are reproduced per minute by the 20th week, and by the time of birth, some 200 billion have been created.

The number of brain cells produced is more than any individual needs. Overproduction is nature's way of ensuring enough cells to handle the development of the numerous complex skills needed for survival. Before birth, the job of the brain cells is to get acquainted with the body that is developing around them. Cells do this by sending out connectors—axons and dendrites—which branch and make connections with other brain cells. About half of these cells die before birth—many because they fail to connect to some part of the developing body, and others through a pruning process that eliminates flawed neural connections.

During pregnancy, especially around the twentieth week, risk factors such as vitamin deficiency, smoking, alcohol, certain chemicals, or too much heat can prevent proper neural development or cause damage to neurons and their connections.

Brain cells continue to multiply after birth, but the production ceases before the end of the first year of life. After age one, humans never get another brain cell. All the brain cells they will ever need and all they will ever have are in place. The mass of the brain, however, is only about one-third that of the adult brain. The brain becomes bigger after birth because brain cells grow in size and because the webbing of connections between and among cells increases. New connections increase in number in the brain as a result of experience.

## The Brain's Filing System

By birth, the brain has organized itself into more than 40 different functional regions that broadly govern such things as vision, hearing, language, and muscle movement.

The brain processes incoming sensory data into and through the functional regions. The processing is done as the sensory data enter through the avenues of the five senses—all that we see, hear, feel, smell, and taste. The five senses are the brain's only way to obtain data about the "outside" world. To enhance the input, the brain constructs motor mechanisms that improve the gathering of information. This enhancement ranges from simple and automatic reflexes to thoughtful and deliberate explorations.

When an event in the environment surprises the viewer, e.g., something is seen that was never seen before or something happens that cannot be explained easily, eyebrows are raised and eyes widen. This simple, automatic facial reflex takes place whenever someone is surprised. Raising the eyebrows is the brain's way "opening the window" to let more light into the eyes and to increase the range of view. Widening of the eyes allows more visual information to enter the brain.

When something attracts the brain's attention, the brain may command the arm and hand muscles to reach out and grasp the curious object, to turn it, feel it, and test it in other ways. The reception of these thoughtful and deliberate exploratory actions is processed into the brain's mapping systems.

As the perceptual sensory data enter the brain, the data are fragmented and distributed to functional regions according to the general type of data the region records. For example, the non-language, sensory perceptions of the world are categorized in many different places: shapes are stored in one place, color in another; movement, sequence, and emotional state are all stored separately.

The neural processes that record the interaction between the brain and the event constitute a rapid sequence of numerous micro-perceptions input and microphysical actions output that take place almost simultaneously. Each occurs in separate functional regions of the brain and each is comprised of additional subdivisions. Visual input, for example, is segregated within the visual mapping region near the back of the brain into smaller systems that specialize for color, shape, and movement. These subsystems also subdivide. At the molecular level, neurobiologists have found that one set of brain cells recognizes perpendicular lines, another only lines slanted at a one o'clock angle, another at two o'clock, and so on.

As a data storage system, the brain takes countless numbers of images, disassembles them into their parts, and stores the parts in specialized brain cells. The benefit of this reduction strategy is that one cell can be called upon many times to identify a similar factor, e.g. whether something is horizontal or vertical. This one cell can recognize vertical in diverse objects such as a building, book, or pencil. Each brain cell has the capacity to store fragments of many memories. These memories or characteristics of the world are broken down into their elemental parts—photons of light, molecules of smell, vibrations of sound waves—ready to be called up when a particular network of connections needs to be activated.

As with the storage of non-language information, aspects of language are also stored in various parts of the brain. Auditory, oral, visual reading and writing capacities are stored separately. The names of natural things, such as plants and animals, are recorded in one part of the brain; the names of objects, machines, and other human-made items are stored in another. Nouns are separated from verbs, and phonemes from words.

As the brain files away the perceptual information, it also constructs connections among the cells in the storage areas. The connections provide an organization of the relationships among different storage areas and are activated as systems and subsystems: *objects*, including their individual

characteristics; *events*, the sequences of movements in time and space; and *actions of the learner*, what was done to an object and what happened as a result. An activated system is a construct of a concept, principle, or other idea.

From what neurobiologists have learned, it is evident that there are no pictures stored anywhere in the brain. The brain is not a camera-like device that stores detailed photos of what is seen. There is no such thing as a photographic memory. It is also not a recording device that stores and plays back what it hears. There are only patterns of connections within the brain, as changeable as they are numerous. When triggered, the connections that have been constructed reassemble the parts into the patterns that make up a memory (a concept, event, etc.). The quality of the reassembly depends upon the quality of the original input.

## Making Connections

In general, enriched environments increase the number of brain connections. Connections are created when an individual becomes curious about something and is free to explore that curiosity. At such times, brain cells sprout thousands of new connectors—dendritic spines that grow out like tree branches. Any one cell can generate hundreds of thousands of connectors during its lifetime. The brain makes the new connectors available for the processing of sensory data and for incorporating that data into prior knowledge constructions.

Enriched environments, varied experiences, and piqued interest around a central topic stimulate the production of connectors, thus allowing for more storage options in response to the experience. Even a slight change for a learner, such as changing to a new seat in the classroom, will cause the brain to generate new dendritic branches and spines as it attempts to incorporate the new viewpoint and new relationships that the learner experiences among objects and people in the classroom. The brain adapts itself in order to cope with changes it encounters in its environment.

New connectors are not necessarily permanent. They gradually become permanent by being revisited—repeating the activity (practice), exploring the activity with some variation (rehearsal), or reflecting on the activity by talking about it. If the connections are not revisited, they may disintegrate and be lost forever. The adage “use it or lose it” applies most certainly to the establishment and retention of connectors within the brain.

The quality of the connections and the extensiveness of the connections within the brain’s systems constitute how well something is understood or how well an individual can perform. Evidence indicates that the more connections you have, the better you are able to solve problems, think clearly, and understand events. The number of connections the brain constructs depends on the individual’s interest in participating in an experience.

Generating the growth of dendrites, the thread-like extensions that grow from neurons (brain cells), is important. When dendrites grow, neurons make more connections to other neurons. When information within a dendritic system is reinforced through practice or rehearsal, the connections gradually become stable, permanent, and usable.

Increasing proper connections among the brain’s neurons results in a better functioning brain. These connections result, in part, through inherited growth patterns within the genetic makeup of a person. They also develop in response to stimuli in the environment that the brain encodes as nerve impulses. The implication here for educators is obvious. Since brains increase dendritic growth as a result of enriching experiences, and since growth is stabilized by practice and rehearsal, the school environment can and should provide such experiences. Doing so will help students retain what they have learned and increase the likelihood of their being able to apply that learning to new situations.

## Education, Aging, and the Brain

Researchers have found that as people climb the educational ladder, the branching connectors between and among brain cells (dendritic material) dramatically increase. Autopsy studies of brains found that very young children have fewer connectors than school-age children. University graduates who remained mentally active had up to 40 percent more dendritic material than the brains of high school dropouts. The brains of university graduates who led mentally inactive lives had fewer connectors than those of graduates who never stopped being mentally active (Kotulak, 1996, p. 18).

Some studies have shown that whenever the brain is challenged, at any time in life, brain cells sprout new dendrites. If a person is healthy, he or she can learn something new at any age by generating new connectors and integrating them into prior structures. A 70-year-old can learn a new profession if interested in doing so. The ability to learn is possible throughout our lives. A surprise

bonus of an active brain that continues to learn is that it may be better protected against some diseases. Scientists have found that educated brains—those with more connectors—better withstand the destructive attacks of Alzheimer’s disease.

The mistaken belief that mental ability declines with age has established an unfortunate stereotype of elderly people. Mental decline is not a fact of aging. Imaging scans show that the cerebral cortex—the thinking part of the brain that controls memory—shrinks by only 10 percent between ages 20 and 70. And the loss of brain cells is modest, occurring only in certain parts of the brain and not throughout. As we age, response time may become slower, but not significantly. It may take longer to remember some things or to solve complex problems, but the power to think remains the same.

However, brain scans show that older people employ different problem solving strategies than do younger ones. Older people more often use the prefrontal cortex. The prefrontal cortex enables a person to consider numerous aspects of a complex problem at the same time, thus increasing the likelihood of deriving a satisfactory solution to the problem. It also enables the individual to develop long-term plans and strategies to attain a goal and to adjust the plans to incorporate new contingencies as they arise. These capacities distinguish “older” brains from “younger” brains.

By piecing together research information obtained from anthropologists, biologists, neurobiologists, psychologists, and psychobiologists, we know that learning depends on the use of our physical attributes: how our hands manipulate objects to find out about them, how our head tilts and turns to let our eyes and ears take in information, and how our body shifts and moves through space.

We are not born with our thinking capabilities completely in place; they develop sequentially over time, and through our interactions with objects in the environment. There is a biological foundation for all human thinking.

## **Biological Attributes and Thinking**

With a head that swivels and tilts and eyes that perceive color and depth, the human body is built to move about and explore unknown territory. The upright stance frees the forelimbs, and the hands, with their opposable thumbs, can manipulate the environment. These biological attributes enable us

to explore our environment, note what happens, and then based on our observations, alter our understanding of it. There is no separating the intricate relationship of bipedalism, hand manipulation, sensory input, and brain development. Their interdependency is important to us throughout our lives.

In much the same way that young children observe objects in their environment by looking, touching, listening, tasting, smelling, and throwing them, adults observe objects on the surface of Mars with remote probes. A TV eye “sees” what it can see. A mechanical hand touches the surface and “feels” the surface. Antennae “listen.” Sensors “smell” the atmosphere. With each of these actions—the youngster’s firsthand, sensory experiences and the adult’s inventive extension of the senses—humans gather knowledge about the universe.

Educators have long praised the hands-on approach to teaching. But in spite of the praise, a visit to most classrooms reveals a different environment in which learning is taking place. Books replace experience very early and are almost the exclusive way by which students are taught from grades 4 through 12. When not doing assignments in books, children spend time listening to teachers or responding to their questions. Classrooms are primarily environments in which symbols are manipulated and substituted for experience.

Books are important. We can learn from them. But books can only do this if our experiential foundation is well prepared. To learn geometry, we must have experience in handling geometric forms and comparing them for similarities and differences. To learn about electricity, we must explore relationships among cells, wires, and bulbs. To read a word on a page, we must first have a concept for the word within ourselves.

At one time the particular biological adaptations that enabled humans to generate, hear, and recognize sounds were important for survival. It took a long time for humans to invent ways to convey information using marks as symbols. Humans were not biologically designed for the purpose of reading or writing or for creating art and music. Reading and writing are fortunate extensions of biological attributes that were designed for other purposes (Pinker, 1994).

Expert teachers never forget that it is only by using the senses that students come to learn about the world around them.

## Biological Stages and Thinking

Compared to other living organisms, humans enter this world quite empty-headed in terms of content. Many species of birds, fish, and other animals are born with brains preprogrammed with information that enables them to survive, gather food, and reproduce their own kind. For example, some migrating birds can travel to locations where they have never been before, which improves their chances for survival. Other animals also behave in instinctual ways that are independent of learning. But the human baby is quite helpless. It must construct its knowledge of the world for itself.



From a biological perspective, not being born with prior knowledge is superb. It strengthens a species' ability to survive. Humans can reproduce their kind in virtually any environment, and the offspring will learn that environment through observations and interactions with it. Instead of coming into life "prepared" with prior knowledge, we have been endowed with a powerful genetic gift—a set of *thinking capabilities* that are programmed to appear at intervals, and that are spaced well enough apart so the current capability has time to establish itself. The power of these capabilities is that they allow us to learn how to survive in practically any environment.

These capabilities are like a series of transparent maps superimposed one on another to depict an increasing complexity of surfaces, streets, cities, terrain, and continents. But they are maps without content: the names, terms, and qualities do not come with the maps. The individual's interactions with the environment gradually fill in the content—first with one map, and then with others.

The nature of thinking capabilities and the sequence in which they appear have been well established on two research fronts. The *biological* basis underlying their appearance is established by periodic increases in brain size (Epstein, 1974), brain weight (Epstein, 1974), cellular growth within

the brain (Winick and Ross, 1969), electrical functioning within the brain (Monnier, 1960), head circumference (Eichorn and Bayley, 1962), general brain development (Restak, 1980; *Scientific American*, September 1992), and evidence of brain reorganizations in roughly two-year cycles (Wright, 1997).

The *psychological* basis is established through evidence of the individual's capacity to deal with independent ideas and to relate them in increasing combinations in two- or three-year spurts from about age 3 through 17 (Pascual-Leone, 1970; Case, 1974). It is also established through the individual's tendency to exhibit the same kinds of behaviors as other individuals within two- to three-year ranges and, as they grow older, to replace each view by a more sophisticated view (Piaget, 1969). Although researchers have provided various descriptions of the unfolding of the thinking phenomenon (Bruner, 1966; Erikson, 1950; Gagne, 1970; Vygotsky, 1974), the sequence in this monograph is described in terms of classroom usefulness.

## Pattern-Seeking Stages of Development

The processes of pattern seeking lie at the very heart of human learning and set humans apart from most primates and other animals. Scientists use the processes whenever they define scientific concepts or develop taxonomies. Each of us uses them frequently, since every word we speak, hear, read, write, or think denotes a group or class of objects or ideas. In an attempt to understand our world, humans have become proficient in these processes, making them the most powerful tools we have for producing and arranging information about our world.

In its *behavioral* form, pattern seeking is exemplified by the ways through which we make sense of our environment by realizing "what things go together." In its *cognitive* form, it is the ways through which we mentally structure the sensory input from our environment. Many psychologists believe that the behavioral and cognitive forms are tightly interwoven because early organizational abilities, such as sorting and grouping, appear to be required before effective conceptualization can take place.

It is known that in the early stages of development, children tend to be perceptually oriented and seem to be able to sort objects on the basis of certain characteristics, but not others. For example, in our culture the ability to sort objects on the basis of *color*



is the earliest to appear. By age seven, the ability to sort by *shape* is predominant (Goldman 1963). Sorting by such characteristics as *pattern* is next, and then *size*

(Johnson 1969). The sorting of objects by the materials of which they are made or by other abstract characteristics, such as molecular structures, develops much later.

It is also known that at early stages, children group objects on the basis of *single characteristics*. The ability to use two or more discrete characteristics simultaneously as a basis for classifying is a higher level process that most children are not able to perform until about the fourth grade. Thus the ability to group objects by single perceptual characteristics develops early, and then becomes less important in the child's organizational repertoire. The ability to group by more than one characteristic

simultaneously, or to group by abstract characteristics that are relatively autonomous of personal experience, develops later. It should be noted, however, that although early abilities recede into the background, they never disappear completely. They become incorporated with more advanced levels and are not independent of those levels. Some become less useful to the individual as more effective forms of organizing take their place. They are never lost, however, and an individual may sometimes return to basic organizational abilities in order to grapple with a new situation.

Some disagreement still exists about the placement of specific, identified abilities in the developmental sequence of our pattern-seeking abilities. The following ideas represent only the identified abilities for which there is a broad agreement in findings among independent researchers as to the order of development (Piaget, 1964; Kofsky, 1966; Allen, 1967; Hooper and Sipple, 1974; Kroes, 1974; Lowery, 1981a).

<b>ORDER OF DEVELOPMENT OF PATTERN-SEEKING ABILITIES</b>			
<b>GENERAL DESCRIPTION</b>	<b>LOWERY'S DESCRIPTORS</b>	<b>RESEARCH DESCRIPTORS</b>	<b>PIAGET'S DESCRIPTORS</b>
<b><u>PRESCHOOL LEVEL 1</u></b> No ability to impose intent upon objects	Repertoire building: learning characteristics (size, shape, color, etc.)	Accidental representation	Sensory-motor operations
<b><u>PRESCHOOL LEVEL 2</u></b> Ability to put two objects together on the basis of a single property	Learning by one-to-one correspondence	Resemblance sorting	Pre-operational stage
<b><u>PRIMARY LEVEL</u></b> Ability to put all objects together on a consistent, single property rationale	Putting things together; returning things to the way they were	Consistent or exhaustive sorting	Early concrete operations
<b><u>UPPER ELEMENTARY LEVEL</u></b> Ability to coordinate two or more properties or concepts at a time	Simultaneity of ideas	Multiple membership classifying	Late concrete operations
<b><u>MIDDLE SCHOOL LEVEL</u></b> Ability to conceptualize ideas that are remote in time and space	Superordinate/subordinate relationships	Inclusive classifying	Early formal operations
<b><u>JUNIOR HIGH SCHOOL LEVEL</u></b> Ability to reason w/permutations	Combinatorial reasoning	Horizontal reclassifying	Middle formal operations
<b><u>HIGH SCHOOL LEVEL</u></b> Ability to reason w/relationships among progressively superordinate ideas	Flexible thinking	Hierarchical reclassifying	Late formal operations

## Inability to Impose Patterns

### Stage 1: Accidental Representation

The way thoughts are structured during the first stage of cognitive development is best revealed through observing what children do. When given objects to play with, the child will explore them *one at a time*, attracted by their perceptual features. When the child has finished exploring an object, it will be discarded.

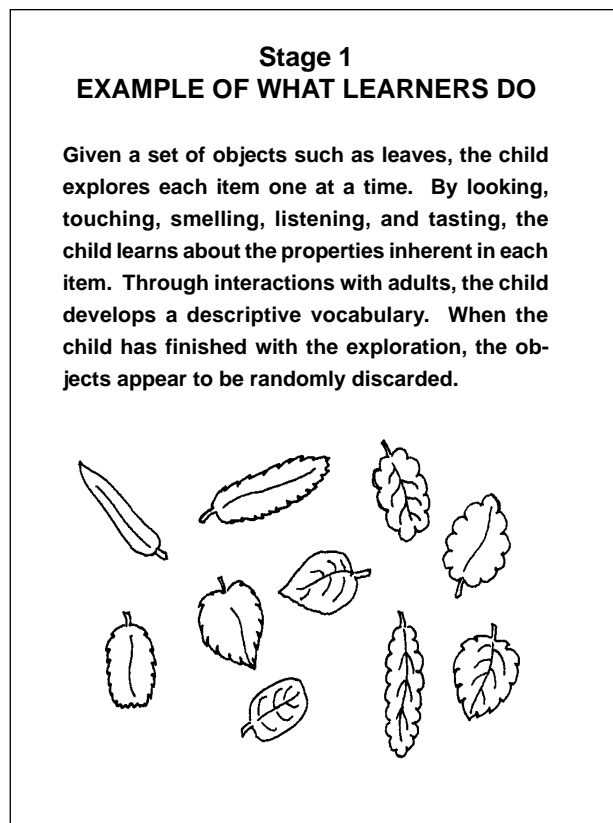
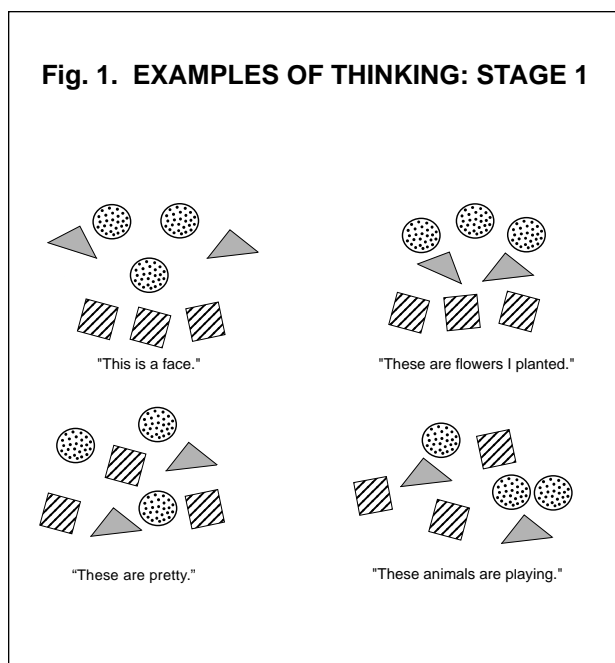
The thinking capability at this stage is highly sensory, and actions are imposed on the object one at a time: looking at it and perceiving aspects of color, size, and shape; touching it and sensing texture and firmness; pushing, pulling, or throwing it and noting how it behaves from such actions; tasting it and noting its flavor, firmness, and texture. These experiences provide the fundamental repertoire for future stages.

Biologically, we are given about three years in which to establish the basic repertoire of the environment in which we live. In addition, the brain is designed to encode words easily in our early years. Children will encode, on average, about 10 new words every day between ages two and five (Jackendoff, 1994). Very young children actively and vigorously construct concepts and associate those concepts with words. Even at this early stage, children can be seen deliberately carrying out inquiry processes that contribute to building the child's personal repertoire.

From birth until about age three, the child explores objects randomly and indicates no system that suggests an organized, rational plan, although the final arrangement of objects might be a design or might accidentally represent something such as a face or train. For this reason, this stage has been described by researchers as the Stage of Accidental Representations. Children at this stage often create similar arrangements to those shown in Figure 1 and give similar accompanying statements.

Because an arrangement of objects by a child may suggest to an adult a classification on the basis of some attribute (e.g., two yellow objects might be placed next to each other), the child's verbal justifications must be checked to determine whether or not a classification ability was used (i.e., the two yellow objects may be placed together by accident).

Children at this stage do not arrange objects to represent something. If in the process of arranging the objects, however, the arrangement begins to look like something familiar to the child, the child may name or give an explanation for the arrangement. Thus, this level is distinct from other levels in that the child does not think about imposing patterns upon objects.



## Pre-Patterning Abilities

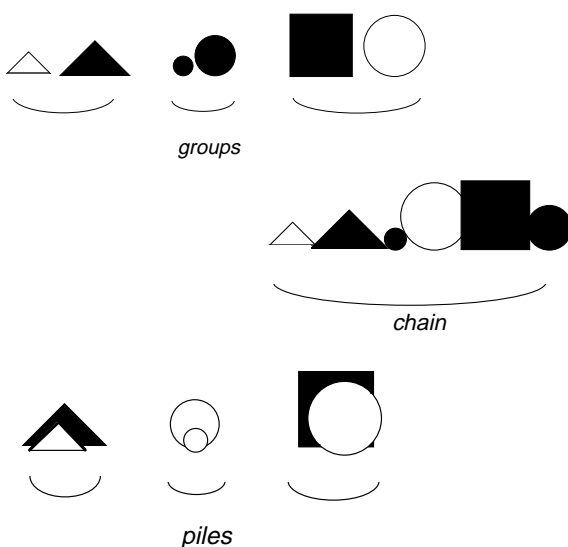
### Stage 2: Resemblance Sorting

The second stage of cognitive development begins to unfold at about age three. Now, when the child thinks about objects and acts upon them, she produces pairings on the basis of size, shape, color, or other properties. Her rationale for each pairing is derived from the repertoire she has acquired through previous experiences. From this action, she establishes additional mental constructs about the world and how the objects and events in it are related. All her thinking is characterized by the ability to match *two objects* together on the basis of one common attribute, or to link two events on the basis of one relationship. This continues to be the dominant way in which she thinks and solves problems until about age six (Kofsky, 1966; Allen, 1967; Lowery, 1981a).

This stage of ability is characterized by the child's ability to compare one action with another, or to pair objects on the basis of one property such as color, shape, or size. The thought is carried out in advance of doing the pairing.

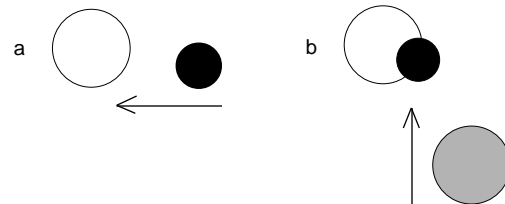
Without prior instruction, children at this stage can be seen pairing objects in one-to-one correspondences because the objects resemble each other. The pairings appear as groups, piles, or chains of objects that allow the child to make basic comparisons of single attributes.

**Fig. 2. EXAMPLES OF THINKING: STAGE 2**



Whenever a student places more than two objects in a group, the placement is usually accomplished by a logic that involves a series of successive pairings. The youngster's explanation usually goes something like this: "I put this round one with this round one (a). Then I put this round one with this set of round ones (b)."

**Fig. 3. EXAMPLES OF THINKING: STAGE 2**



To accomplish the second step, the child mentally combines the first two into a single concept, then adds the additional piece to it as if making a one-to-one match. This collapsing of quantities (e.g., 2 yellow objects when paired become 1 set) is important, for later it enables the child to deal with larger quantities of objects. The collapsing of quantities into smaller numbers enables the human brain to deal with greater quantities of objects or events within its environment.

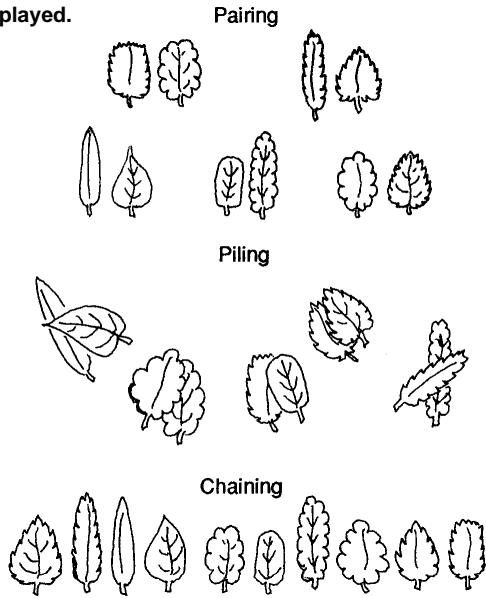
Although children can put all matching objects together, they do not do so by conceptualizing the "match" before moving the objects. Instead, they move the objects by trial and error, then afterwards may recognize the concept.

Children at this stage do not put together all the objects that belong together without going through a sequence of steps. And although children can recognize several different properties, they do not yet use them in combinations (i.e., multiple properties) at the *same* time.

Card games that children enjoy and have success with at this stage are Slap Jack, Concentration, and the newer variations of the traditional Old Maid card game.

**Stage 2**  
**EXAMPLE OF WHAT LEARNERS DO**

Given a set of objects, such as leaves, the student matches a familiar object with a new, unfamiliar object on pairing or one-to-one basis. When the student has finished with the action, pairs of objects or piles or chains linking pairs together are displayed.



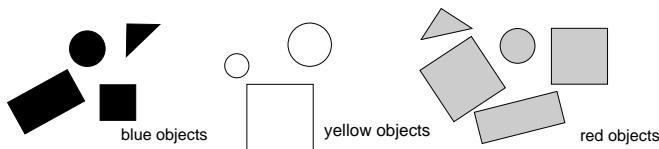
**Stage 3: Consistent and Exhaustive Sorting**

The next stage of cognitive development begins at about age six and is established for most children by age eight (Lovell and others, 1962; Smedslund, 1964; Bruner and Kenney, 1966).

Arrangements made by a child will use up (exhaust) all the pieces in a set. When grouping objects, the child will give a rule that is logical (consistent) for all the objects within the set. For example, if the child puts all the blue objects together from the array of objects, the child will continue to sort the yellows, reds, and other colors into groups and say, "I've grouped all of these by their colors."

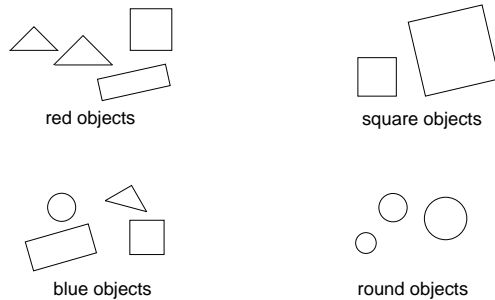
The sorting ability at this stage is characterized by the child's grouping of *all* objects in a set on the basis of *one* common attribute.

**Fig. 4. EXAMPLES OF THINKING: STAGE 3**



If earlier experiences have been rich, children at this stage have acquired a broad repertoire of possible properties that make up objects. They can sort objects to the extent of that repertoire. Each sorting, however, is always on the basis of one property, because children cannot yet mentally combine more than one property at a time. Evidence of this stage appears in children's creative writing, where each adjective used to describe something is placed in its own sentence ("It is an *old* house. It is a *brown* house. It is an *empty* house.") or is chained together with connectors ("It is an old *and* brown *and* empty house."). Children in transition from the previous stage will often mix their logic for groupings as shown below.

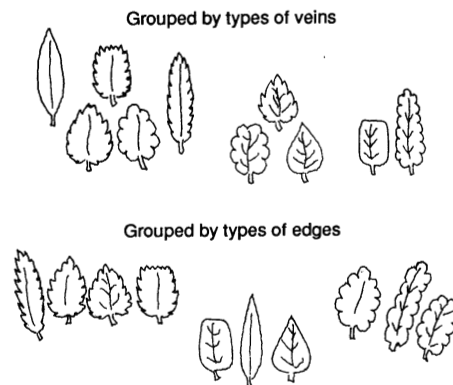
**Fig. 5. EXAMPLES OF THINKING: STAGE 3**



A card game that children readily learn and play successfully at this stage is Fish, a game where sets are collected (all four Aces, all four 7s, etc.). A child at this stage is often frustrated when playing with a child at the previous level who only saves two cards in each set.

**Stage 3**  
**EXAMPLE OF WHAT LEARNERS DO**

Given a set of objects, such as leaves, the student groups together or takes apart sets of objects based upon a single, consistent rationale. When the action is finished, sets of objects have a logic to their arrangement.





## Stage 5: Inclusive Classifying

Thinking about the relationships among groups of objects and a superordinate conception of them are indicators of this stage of development. It appears at about age 11. Such thinking realizes that if one collection of objects is included in another, then all the objects in the smaller grouping are but a part of the larger. Conversely, a part of the larger class contains all of the smaller. There is recognition that the whole is equal to the sum of its parts and that an example to represent the whole does not exist.

One characteristic of this stage of thinking is the emergence of deductive reasoning, which allows students to logically make inferences between the more general and the less general:

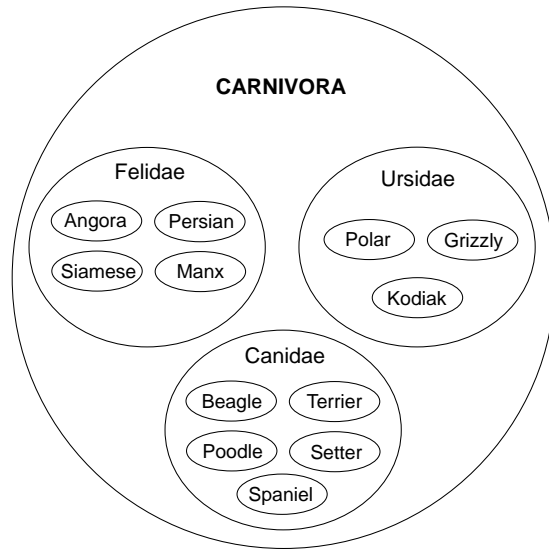
*All women are mortal.  
All queens are women.  
Thus, all queens are mortal.*

Given the opportunity, the student can learn to recognize logical relationships between larger and smaller classes.

The patterning ability of the student at this stage is characterized by the inclusion of one or more classes of objects within a superordinate class of objects. The student recognizes that the whole (larger class) is equal to the sum of its parts (the subclasses) and that there is a logical relationship between the larger and smaller classes. For example, the student realizes that all whales are mammals but that not all mammals are whales.

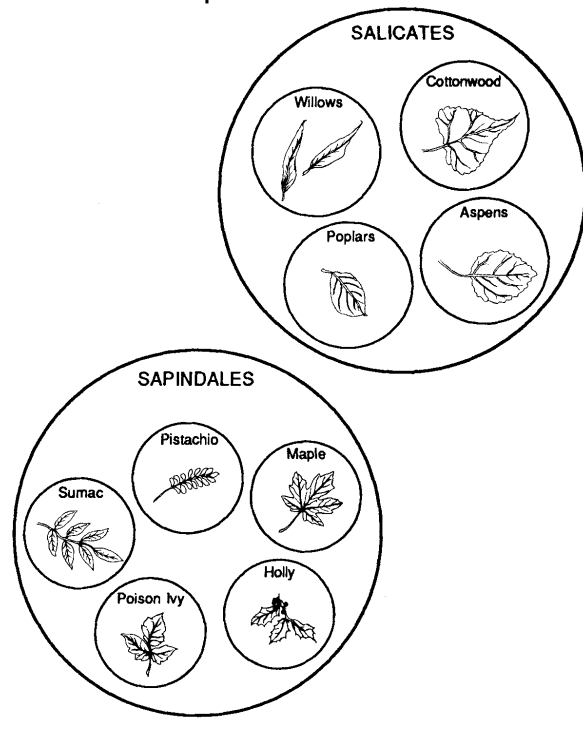
It is at this stage that students can fully understand that they live in a particular city *and* a particular state at the same time, *and* that one is superordinate to the other.

Fig. 7. EXAMPLES OF THINKING AT AGE 11



### Stage 5 EXAMPLE OF WHAT LEARNERS DO

Given a set of objects, such as leaves, the student abstracts multiple commonalities among them, thus achieving a superordinate concept that relates them all together. When the student has finished, a collection of objects has been arranged and described for its abstract qualities.



## Flexibility in Patterning Abilities

### Stage 6: Horizontal Repatterning

As the next stage unfolds, at about age 14 (Lawson and Renner, 1975; Lowery, 1981b), the student becomes more flexible in her thinking. An individual at this stage can classify objects by one or more attributes, then reclassify them in numerous different ways, realizing that each way is possible at the same time and that the choice for an arrangement depends upon one's purpose.

For example, if an individual is given a set of books with the identifying characteristics of size (number of pages), shape, color, and content, the individual realizes that the books can be organized on the basis of:

- 1 size; shape; color; content;
- 2 size and shape; size and color; size and content; shape and color; shape and content; color and content;
- 3 size, shape, and color; size, shape, and content; shape, color, and content; and
- 4 size, shape, color, and content.

Given the goal of locating information, the individual selects only the content as the organizing attribute because the other attributes are not useful in achieving the goal. Given a different goal, such as the determination of the ratio of books with fewer than 100 pages to those with more than 100 pages, the individual reclassifies the books for a different attribute to achieve that goal.

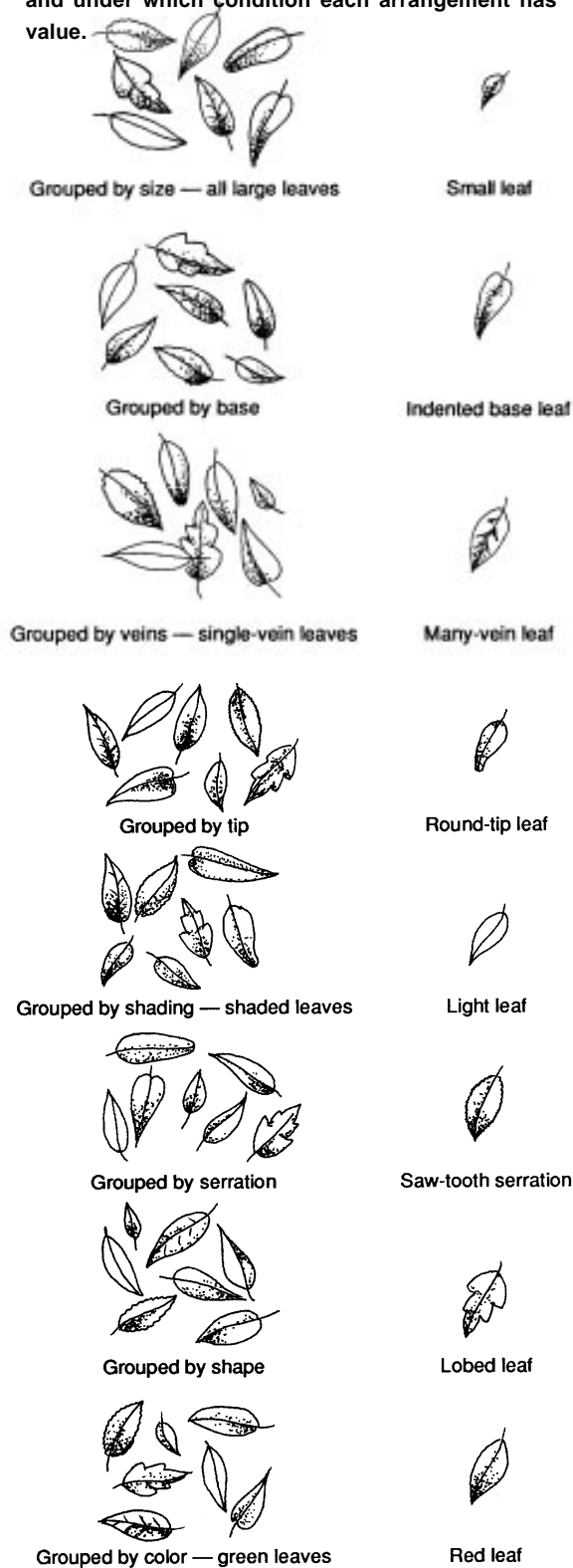
**Fig. 6. EXAMPLES OF THINKING: STAGE 6**

Combinatorial thinking enables students to determine whether or not a conclusion derived from a set of premises is logically valid. If they are interested in the relationship between two variables, such as studying hard and getting good grades, they recognize that there are four possible combinations of the two variables:

What Students Can Do	Consequences of the Action
A. study hard .....	receive good grades
B. study hard .....	don't receive good grades
C. don't study hard .....	receive good grades
D. don't study hard .....	don't receive good grades

### Stage 6 EXAMPLE OF WHAT LEARNERS DO

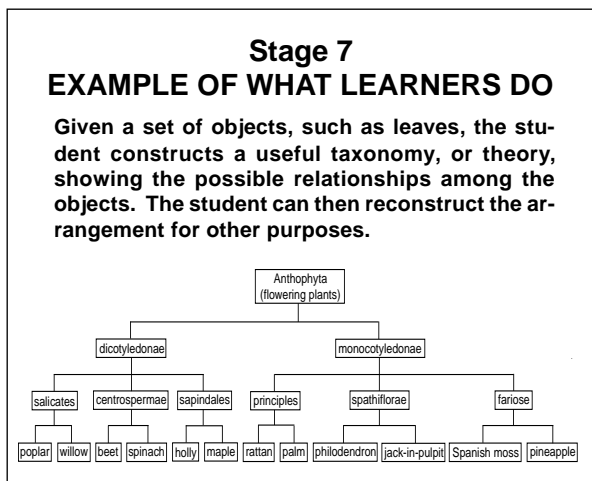
Given a set of objects, such as leaves, the student classifies, takes apart, reclassifies, and continues to do so throughout all the possible combinations of classes that can be created with the objects. When finished, the student describes the various classes and under which condition each arrangement has value.



## Stage 7: Hierarchical Repatterning

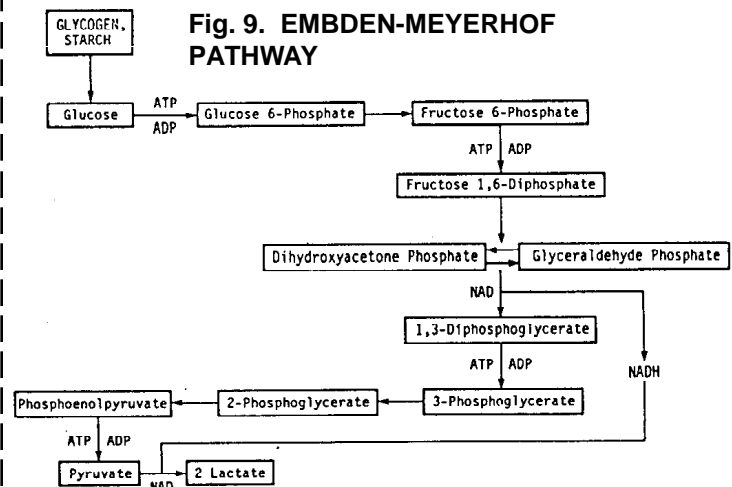
When the seventh stage appears at about age 16 (Karplus and Karplus, 1972; Lowery, 1981a; Lowery, 1981b), the student is able to develop a framework based on a logical rationale about the relationships among the objects or ideas, while at the same time realizing that the arrangement is one of many possible ones that eventually may be changed based on fresh insights.

This stage is characterized by an individual's ability to classify and reclassify objects or ideas into hierarchies of increasingly related or inclusive classes.



At this stage of ability, a content expertise is necessary. An individual can develop a theoretical framework based upon a logical rationale concerning the relationships among the objects or ideas comprising the framework. At the same time, the student realizes that the arrangement is tentative, one of many possible arrangements that may be changed upon fresh insights. The patterning that the human mind is capable of doing at this stage is complex and is expressed in many different ways. The patterns created exemplify the highest order of flexible thinking.

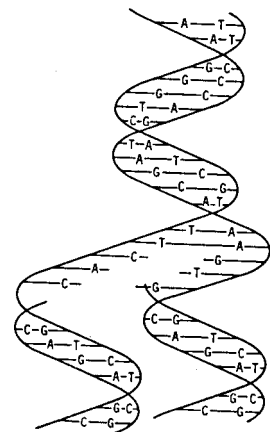
**Figs. 9, 10, 11: EXAMPLES OF THINKING: STAGE 7**



**Fig. 10. PERIODIC TABLE OF THE ELEMENTS**

1																	18															
H 1.0079																	He 4.0026															
3	4															10																
Li 6.941	Be 9.0122															Ne 20.18																
11	12															18																
Na 22.99	Mg 24.305															Ar 39.948																
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36															
K 39.098	Ca 40.078	Sc 44.956	Ti 47.88	V 50.942	Cr 51.996	Mn 54.938	Fe 55.847	Co 58.933	Ni 58.693	Cu 63.546	Zn 65.39	Ga 69.723	Ge 72.61	As 74.922	Se 78.96	Br 79.904	Kr 83.8															
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54															
Rb 85.468	Sr 87.62	Y 88.906	Zr 91.224	Nb 92.906	Mo 95.94	Tc 97.91	Ru 101.07	Rh 102.91	Pd 106.42	Ag 107.87	Cd 112.41	In 114.82	Sn 118.71	Sb 121.76	Te 127.6	I 126.9	Xe 131.29															
55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86															
Cs 132.91	Ba 137.33	La 138.91	Hf 178.49	Ta 180.95	W 183.84	Re 186.21	Os 190.23	Ir 192.22	Pt 195.08	Au 196.97	Hg 200.59	Tl 204.38	Pb 207.2	Bi 208.98	Po (209)	At (210)	Rn (222)															
87	88	89	104	105	106	107	108	109	110	111																						
Fr (223)	Ra (226)	Ac (227)	Rf (261.1)	Ha (262.1)	Sg (263.1)	Ns (264.1)	Hs (265.1)	Mt (266.1)	Unn (267)	Unu (269)																						
																		58	59	60	61	62	63	64	65	66	67	68	69	70	71	
																		Ce 140.12	Pr 140.91	Nd 144.24	Pm (144.9)	Sm 150.36	Eu 151.97	Gd 157.25	Tb 158.93	Dy 162.5	Ho 164.93	Er 167.26	Tm 168.93	Yb 173.04	Lu 174.97	
																		89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
																		Th 232.04	Pa 231.04	U 238.03	Np (237)	Pu (243.1)	Am (243.1)	Cm (247.1)	Bk (247.1)	Cf (251.1)	Es (252.1)	Fm (257.1)	Md (258.1)	No (259.1)	Lr (262.1)	

**Fig. 11. DNA**



## Educational Implications

The notion of stages is more than the sequential progression of thinking development. It includes the patterning of responses throughout the sequence and the time periods necessary for consolidating each capability. Researchers have found that all humans progress through the seven biologically based stages described here (Inhelder and Piaget, 1964; Kofsky, 1966; Allen, 1967; Hooper and Sipple, 1974; Kroes, 1974; Cowan, 1978). This developmental learning sequence is common to all cultures (Bruner and others, 1956; Prince-Williams, 1962; Lovell and others, 1962; Schmidt and Nzimande, 1970; Wei and others, 1971; Lowery and Allen, 1978; Cowan, 1978). As learners move through the stages, they integrate all learnings acquired during prior stages, including behaviors, concepts, and skills. It also involves the gradual integration of all the prior levels, and the gradual unification of behaviors, concepts, and skills.

The result is a broad structural network of interrelated capabilities appearing, not all at once, but within a fairly narrowly defined period followed by a plateau of several years. For thinking to develop properly, a very long childhood is necessary—one in which the youngster is free from having to carry out survival activities until all the stages are in place. This is why humans have a longer, biologically determined childhood than any other animal on earth. Pierce (1977) said it this way:

Although at any stage of development, nature is preparing us for the next stage, the beauty of the system is that we are conscious of none of this. Ideally, we must fully accept and exist within our developmental stage and respond fully to its content and possibilities. This means that every stage is complete and perfect within itself. The three-year-old is not an incomplete five-year-old; the child is not an incomplete adult. Never are we simply on our way; always we have arrived. Everything is preparatory to something else that is in formation.

The importance of this biological basis for the development of thinking is too often overlooked by educators. The periodic rapid increases in brain growth (perhaps the establishment of cellular networking) coupled with the appearance of new, content-free thinking capabilities (that overlay earlier capabilities containing content) are followed by plateaus (time periods) that allow new capabilities to become integrated, used, and made functional. Unfortunately, the organization of

curriculum and teaching in most American schools and the design of commercial textbooks do not match the thinking capacities of learners. Many topics are introduced at a stage before students can comprehend them. Content is not arranged so it can be learned and built upon over a period of years.

Most teachers are familiar with and trained in the vertical sequencing of content. Skills and concepts constantly increase in complexity as students move through the grades. Curriculum expectations for a student's performance are based on the indices of school grade, chronological age, or achievement scores, rather than upon cognitive development.

In the competitive social context of schools, educators try to accelerate the stages of development through school intervention by moving advanced topics and skills into earlier grades (Furth, 1977). They act as if the distance from childhood to intellectual adulthood is measured only in terms of quantity—as students grow older, they acquire more experience, greater information, and broader knowledge. This is an incomplete view of intellectual growth. The most significant differences between youngsters and adults rest in the nature and quality of their understanding. As youngsters develop, they pass through ways of thinking, each representing a different organization of experience, information, and knowledge, and each leading to a very different view of the world.

In an educational system that matches content inappropriately to student capabilities, many students progressively lose confidence in their ability to learn what has been taught, and eventually resort to memorizing what is expected of them rather than comprehending what is to be learned (Collins, 1974; Covington and Berry, 1976). The reasons for this are highly complex, but two aspects related to the biology of thinking seem clear and proven:

1. The potential for success diminishes in relation to the degree of mismatch between content and thinking capability during a plateau period.
2. As personal evaluation becomes official evaluation in formal schooling, the mistakes and errors that are a natural part of learning become misinterpreted as failures. As a consequence, students become motivated to work for extrinsic, symbolic rewards such as gold stars and grades, or to please adults, rather than for the intrinsic excitement of exploration and learning.

When cognitively mismatched content is accompanied by external expectations and rewards, teachers and schools unwittingly set unrealistic standards for many students. Over time, students are likely to lose confidence and develop a sense of failure. The result may contribute to students experiencing developmental dysfunction, in which case their movement through the learning stages either slows down or stops entirely. Often such students' academic work is good in some areas and extremely poor in others. This is referred to by psychologists as asynchrony (Cowan, 1978).

It is important that curriculum and instruction reflect what is known about the biological basis for thinking. Students perform best in a *horizontal curriculum*, which challenges them to use a particular stage of thinking with different materials at various levels of abstraction. This model allows students at an identified stage of development to explore many experiences within that stage. Teachers do not compare a student's progress with that of other students. Rather, they select worthwhile experiences appropriate to each child's developmental stage, organize them for meaningful interpretation, and orchestrate them to provoke the student's thinking. Numerous researchers have helped to validate this model in the sciences (Askham, 1972; Loggins, 1972; Lowery and Allen, 1978) and in mathematics (Ginsburg, 1977; Langbort, 1982; Rupley, 1981).

The essence of this approach is derived from the biological basis for thinking and learning, which shows that thinking capabilities are independent of the objects involved in a given task. Students experience small, sequential steps of understanding through an inexhaustible set of possible experiences. For example, a teacher might design sorting tasks to challenge a student who is at or beyond Thinking Stage 2 (resemblance sorting). The teacher could ask the student to find two marbles that are alike in color from an array of marbles. The activity can be repeated using size as the feature for pairing two marbles. The activity can also be done with other objects using color or size or other physical properties. In each variation, the thinking capability required remains the same—pairing two objects on the basis of a single property. Studies show that when instructed in this way, students' thinking capabilities become more proficient and transfer more easily to new tasks.

Teachers can also use the horizontal curriculum approach to extend students' thinking into higher levels of abstraction without requiring a higher state of thinking. For example, if a student who is

**Fig. 12. FORMATS FOR LEARNING**



at or beyond Thinking Stage 3 (consistent and exhaustive sorting) can group all objects within a set so that they logically belong together, the action is considered to be firsthand or *concrete* (a). The action involves manipulations of real objects and not abstractions of reality. One cannot say enough about the value of firsthand experiences. A multiplicity of our five senses, the only avenues into the brain, are activated through firsthand experiences. The brain receives and stores, in effect, a record of the neural activity in the sensory and motor systems from each sense when an individual interacts with the environment. Each record is a pattern of connections among neurons that store the sensory data, patterns that can be reactivated to recreate the component parts of the experience at a later time.

The same student is also able to impose the same thinking (consistent and exhaustive sorting) on *pictorial representations* of reality without having to be at a more advanced stage. Pictorial representations are considered to be one step removed from reality because they substitute for the reality (b). Fewer of our five senses are utilized in the study of representations. The use of representations in teaching has great value. A representation of planets in motion provides a way to look at the relationships among the objects within our solar system. Running water through earth materials in a stream table exemplifies the cause and effect relationships that create landforms.

The power of representational instruction is that it can simplify complex ideas (as with illustrations) and truncate space and time (as with simulations). Sometimes representational instruction is important to precede firsthand experiences. Experience with a stream table enables students to better interpret certain landforms in the area where they live. Experiences with modeling circuitry provides prior knowledge for working with electrical circuits. Experiences with building a model of a human skeleton enables the learner to better construct the collection of bones in owl pellets or interpret the arrangement of bones found in an archaeological dig.



Sometimes firsthand experiences are important to precede representational experiences. Various direct studies of plants and animals, rocks and minerals, and balance and motion enhance understandings of videotapes and simulations, and other representations encountered after the studies. Some examples include the showing of plants and animals in more distant natural habitats, simulations of how earth materials are transformed into different forms, and animations of how objects move and fall.

Again, without having to be at a more advanced stage, this same student has the potential to successfully carry out the same thinking on *symbols* or *abstractions* that are several steps away from reality (c). For symbols to carry meaning, the brain must be able to interpret the symbol in terms of prior knowledge. If there is no match between the brain's storage and the symbol, then the symbol cannot be interpreted. The great value to reading books, whether narrative, technical, or expository, is that the words (symbols) are used to take a reader's prior knowledge and rearrange it in fresh ways. What is learned from books is, essentially, rearrangements of stored knowledge. The rearrangements establish new insights, fresh ideas, and conceptual frames through analogies and metaphors that the reader had not thought about previously.

Experiences designed to make use of thinking capabilities may provide significant cognitive and affective benefits by allowing students to perform progressively challenging tasks that are within the realm of potential success. On the other hand, the accelerated and other mismatched vertical schemes may be inviting failure and eroding self-worth.

Our biological heritage provides us with a sequence of thinking capabilities. Originally designed to enhance our chances for survival, the interplay between thinking and actions has brought about understandings about the world that transcend the immediacy of survival. As humans, we have the leisure to fantasize and contemplate. We create through art, music, and architecture; we imagine and communicate through books. We explore frontiers that are beyond the tangible and experiential. Educators must understand the heritage in order to appropriately select and sequence worthwhile experiences for students and to enhance their ability to think well. An understanding of the biological basis for thinking can lead to the conceptualization and implementation of a school curriculum that is far more responsive to the realities of how humans learn and to the intellectual differences among students at all grade levels, from early childhood through adolescence.

Much of the knowledge contained in this monograph can be used in selecting appropriate, effective curriculum experiences for students. Some questions to ask about curriculum materials include:

1. Does the curriculum teach fewer topics in greater depth?
2. Does the program move from experience to abstractions?
3. Does the program emphasize reading about science, or does it involve students in hands-on experiences that can be reinforced with good reading materials?
4. Is the curriculum developmentally appropriate to the students' capacities and to the skills they are to master?
5. Does the curriculum build upon prior learning as it progresses through the grades?
6. Is the curriculum designed so that students can construct ideas on their own by exploring and manipulating the materials?
7. Are students provided multiple opportunities to practice skills they have learned, work with variations of the activities, and reflect upon them through discussion?
8. Was the program tested? If so, how and what was learned and changed?

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## Notes