Using Space to Think

by
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ABSTRACT

This thesis is proposing a research direction of using computation to help people fully take advantage of spatial cognition in thinking process. As our most important form of information processing spatial cognition provides thinking what logical and verbal means are inferior at. But without external aid, its application is tremendously constrained. Computation could play a role in circumventing those constraints and bridging out the strength of spatial cognition in thinking process. This could augment our of thinking ability and reform our mind.

Thesis Supervisor: William L. Porter
Title: Norman B. and Muriel Leventhal Professor of Architecture and Planning

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I want to dedicate this thesis to three persons affecting my personality:

My father, emotional and humanistic of a historian and poet
My mother, creative and active of an architect
Professor William Porter, erudite and modest of a professor

I would like to thank Professor Judson Harward for teaching me Java and awarding me a Research Assistantship, thank Professor William Mitchell for inspiring and encouraging me to explore new theory, thank Professor Jeffrey Huang and Professor Urs Hirschberg for introducing me to the area of Information Visualization.

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Chapter 1 Introduction

In the research field of design and computation, the main trend is to incorporate computation into the design process, which is to use new tools in an exiting area. My research interest lies in bridging architectural thinking, especially spatial thinking to emerging areas through computation. It is research for new concepts which come from the combination of both design and computational thinking; it is research on spatial thinking for its potential applications.

In this thesis I will concentrate on a single topic in this direction – using space to think. It is a study about the role of spatial cognition in abstract thinking process, and how to fully take advantage of spatial cognition with computation as a mean to extend humans' cognition as a whole. It is to propose an open-end research direction but not to develop a specific application.

My interest for this topic comes from two projects I experimented in the course Visualizing Information (GSD2312). From these projects, I did get some sense that computer generated spatial representation form could help people in understanding abstract relationships which are not obvious and intuitive in its own format, and could provide people a better environment for exploring information set. This triggered my interest to study about human spatial cognition and human thought and to find out why this result could happen. In this further study, I gained a deeper understanding of the value of spatial cognition in thinking process and the constraints in its application. I also learned areas where computation could help to circumvent the constraints and make the value of spatial cognition fully exploited.

In the following chapters, I will discuss my research in reference to the research in this area, the two projects I experimented, my study about the value of spatial cognition in abstract thinking, and how to approach this topic with the aid of computation.

The title of this thesis is inspired by the subtitle of "Readings in Information Visualization – Using vision to think" edited by Card et al. The editors use "Using vision to think" to express the subject of that book, which is using the special properties of visual perception to resolve logical problems. My interest lies in the role of spatial perception and cognition in thinking process, thus the title: Using space to think.

Chapter 2 Location in the State of the Arts

Philosophically

There have been studies on the relationship between visual and abstract from the very beginning of philosophical thinking. Many of the philosophers pay much attention to analyzing semantic meanings from visual forms, and use these abstract concepts to aid thinking or to create new visual forms. I think the research on Shape Grammar is in this direction, which gives icons meaning and makes them to be symbols which have relationships among themselves. After analyzed to the level of logic, those symbols are computable. We can then take advantage of the strong logical calculation ability of computing and to generate new visual forms either in response to the requirement inputted from language format, or for novel visual forms which could only be generated beyond the human visual thinking limit.

My research interest is in the opposite direction from the studies discussed above. It is to reduce the abstract level of concepts and logical relationships, and to make them easier to be conceived by being perceived in the spatial visual environment. I consider the two-dimensional diagrams and graphs in Tufte's work as in the half way of this process of moving from abstract to intuitive. Even though they visually present many concepts difficult to conceive, they are still forms abstracted from our thinking and reasoning, not purely intuitive. What I propose is to use a spatial, dynamic, and interactive environment as a medium. This is the medium most intuitive to us, and it is the ultimate context for our intrinsic perception.

Among Multiple Disciplines

My research topic has a multi-disciplinary characteristic and there is no well-defined area it belongs to. During my research, I primarily consulted works on visual and spatial art, spatial reasoning, knowledge representation, parallel computing, memory and mind study, and mental imagery. This study involves areas of philosophy, art, cognitive science, artificial intelligence, and computer science. Each of them covers different topics listed above. Even in cases addressing the same topic their point of view and way of thinking are also very different. In steering my reading and study in such a huge sea of knowledge it is crucial to always be very clear about the specific aim of my research, what I am looking for from that study, and what is the difference between the research I am studying and mine. Keeping my knowledge searching in such an active way enables me to expand the scope my study to more related topics and to gain deeper knowledge from those subjects without being lost in any of them.

There is research on spatial thinking, spatial representation, and spatial knowledge in cognitive science. Their interest is to study what a brain is, its property and functioning, and its limitation. My interest is to develop external aids to extend the cognitive ability based on the knowledge of the cognitive nature.

To computer scientists, understanding how human language maps onto spatial representations is a prerequisite for creating computer systems that can receive human language instructions and carry out human actions. My interest is to use the computer generated spatial structure to help people in abstract reasoning and comprehension.

What interested to Artificial Intelligence in studying the knowledge representation and human mind is to construct human mind on a robot to instruct robot behaviors. My interest is to find ways to help human in their own thinking process, to augment the thinking ability of human mind, in the areas such as memory, inference and discovery.

There is research on spatial reasoning and thinking of spatial knowledge, in which the space is considered as topic and content. In my research spatial structure and relationships serve as environment for the reasoning of other abstract topic.

There is research on the mapping between language space (verbal representation of space) and perceptual space. My interest is not to only research on such existing system, but to explore new applications or potential usability of the perceptual spatial structure in aiding verbal and abstract thinking.

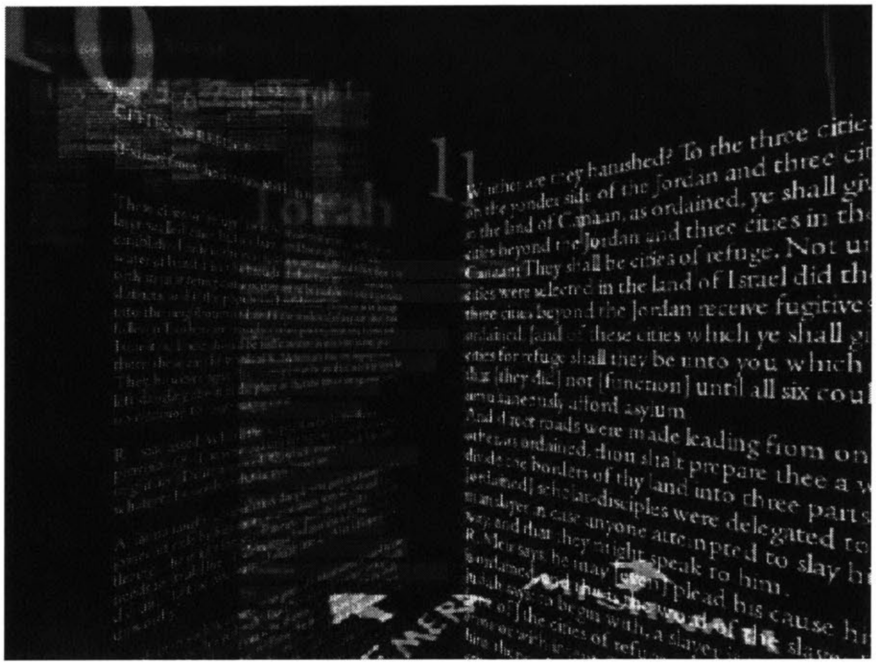
In Information Visualization

My research topic, using space to think, is closely related to 3D information visualization. It particularly refers to the using of spatial visual form to aid people extending their cognitive ability in abstract thinking.

The concept concentrates on how to take advantage of spatial structure in the thinking process from the study of spatial visual perception and cognition. It is different from 3D visualization of physical data, in which data information is mapped onto spatial locations according to their coordinates in reality, like a mirror of the physical world. It is also different from some existing applications which simply substitute nodes in abstract information sets with balls or cube in a 3D space only for eye-catching or appealing effects.

David Small's research is an excellent example of using space to represent non-spatial information expressively. The space in his project is on the "landscape" scale, and his applications use the metaphor of narrative to extend the navigation, while my spatial concept is on a relatively small scale and my applications will be based on people's perception and conception of the surrounding space and their relationship with it.

The spatial thinking at Asymptote Architecture is on the architectural scale, but they haven't reached the level of using space to organize information. Many of their innovative spatial concepts are yet to be employed beyond the stage of exhibiting static images.

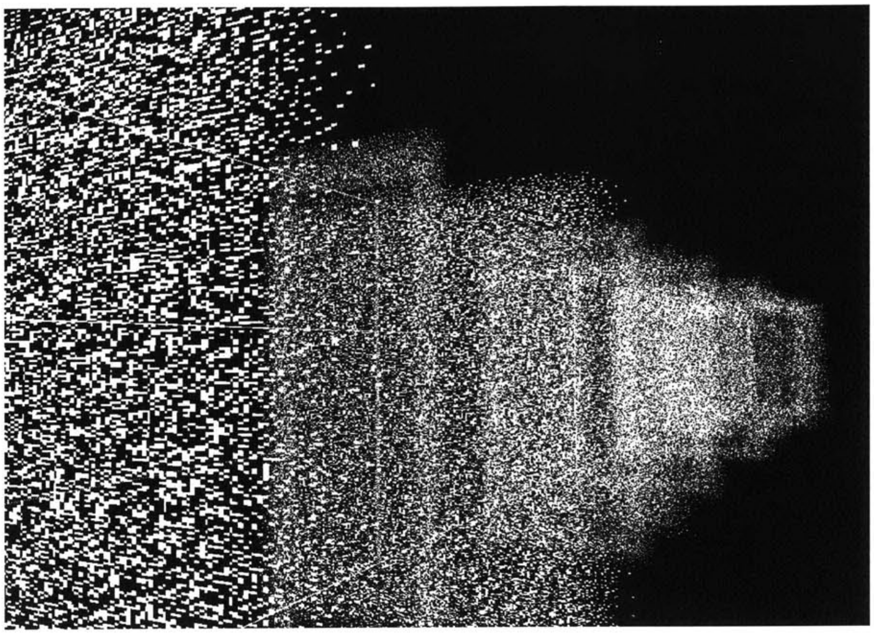


The Talmud Project by David Small. [Image from http://www.davidsmall.com]

In Yanni-Kaklamanis's project, the spatial flux responds to the visitors' movement and gaze, and opens up new spaces at the visitors' gaze point.

[Screenshot by author from http://www.arch.columbia.edu/Projects/Studio/Fall98/Rashid/museums/yanni/kaklamanis1/stage/yanni1.wrl]

In his oscillating space, Ben Aranda tries to achieve a "third space" from the inversion flux and the nullified dialectics.



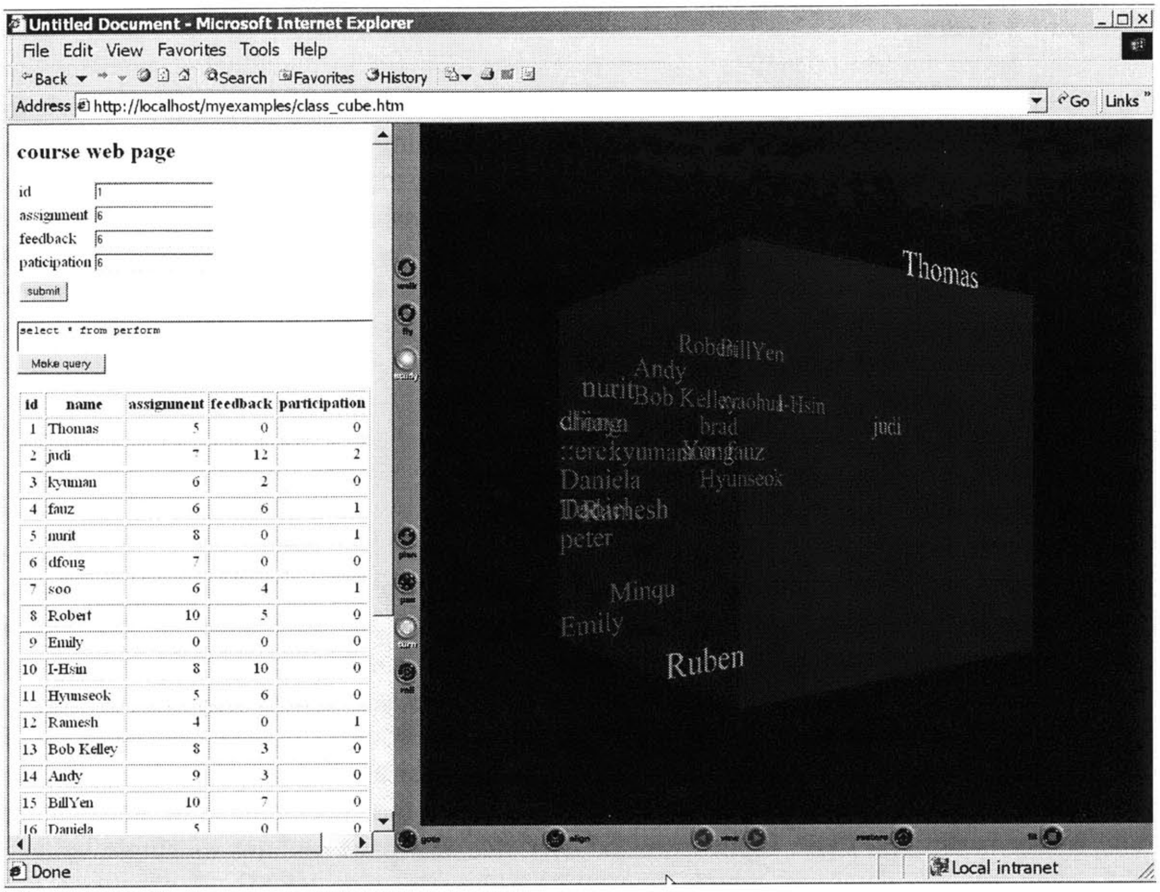
[Screenshot by author from http://www.arch.columbia.edu/Projects/Studio/Fall98/Rashid/museums/bena/aranda2/stage/bena2.wrl]

Chapter 3 From

In the course of Visualizing Information at GSD Harvard, I experimented, through the projects of Class Cube and 3D Tree-map, the idea of using spatial concept in visualizing abstract information. They really verified the hypothesis that spatial visual representation form could help people in understanding abstract relationships which are not obvious and intuitive in its own format, and could provide people a better environment to study massive information within complex structures. This leads my interest to further exploration to discover why this result could happen, why it is not widely used and how to fully exploit its potentials.

Class Cube

In my Class Cube project I use a cube to visualize the relationship of students' performance in the class of GSD2312. The number of homeworks submitted is used as y-axis; the number of votes as feedback from the students and professors in this class is used as x-axis; the number of messages and comments posted (participation) is used as z-axis. This is intended to be as part of the course web site where the information for number of works, feedback and comments is updated through students' participation. In this project I created a test page and a local database for testing purpose. The cube was built in VRML, the database was created in mySQL and the communication between user and server is through PHP. Input from the user-side test page updates its single value in the sever-side test database, which then updates the user-side VRML display with new values for relationship. When adding number of works, feedback, and participation for one student to the form on the test page, he will come out to a more pronounced position in the VRML cube, and the other students will go backward and downward. In such a visuospatial representation, the relative property of the relationship is represented through a vivid perception of the spatial relationships among those entries. No one will explode out of the cube and one student's new improvement will shift down the positions of students who stand still in their study.



Screenshot of the Class Cube application.

3D Tree-map

In my 3D Tree-map project I focus on how to take advantage of the third dimension in visualizing hierarchically structured information. The subject of the project, MIT Process Handbook, encompasses hierarchically structured information. Each node has its attribute of being inside a hierarchy structure; users need this as a hint at some stage of the searching. But users' purpose of visiting this database is for information embedded in each node. Users' further navigation also relies heavily on the information they acquired from the nodes they are visiting, or visited. Thus it would be very important to provide enough display space for the content of each information node. A hint about its position inside the hierarchy structure to aid the navigation is enough in this situation. When approaching the detail and overview problem in 2D medium, there is a forever contradiction. The 2D display space has its limit, the more the nodes in the structure are displayed, the less the space each node is assigned. For example, in Shneiderman's Tree-map concept, even though they make 100% use of the screen place to display the entire information structure, the display space assigned to each node shrinks very quickly based on the hierarchical ratio, children nodes on lower levels are usually too small to be recognized. When introducing the third dimension and the spatial concept, the screen space can be used not only once but infinite times, and thus the display space will be infinite. In the following image, I illustrate how the children nodes on each level are uncompressed to full screen corresponding to the division from Shneiderman's Tree-map concept (the square placed on the top left most), which is recursively dividing the screen space of parent node to its children nodes in proportion to their volumes. Since they are now separated into many screens, we can also divide them in the same orientation, like the corresponding images in the second line.

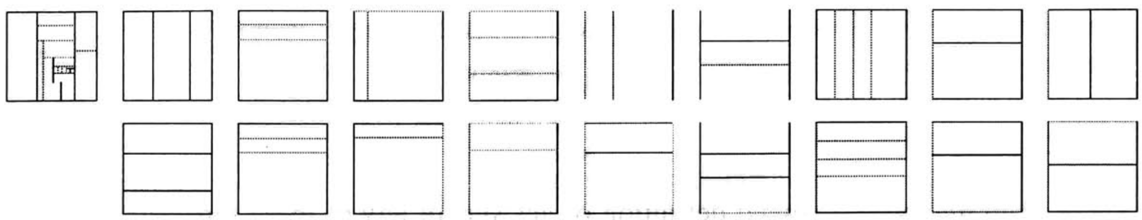
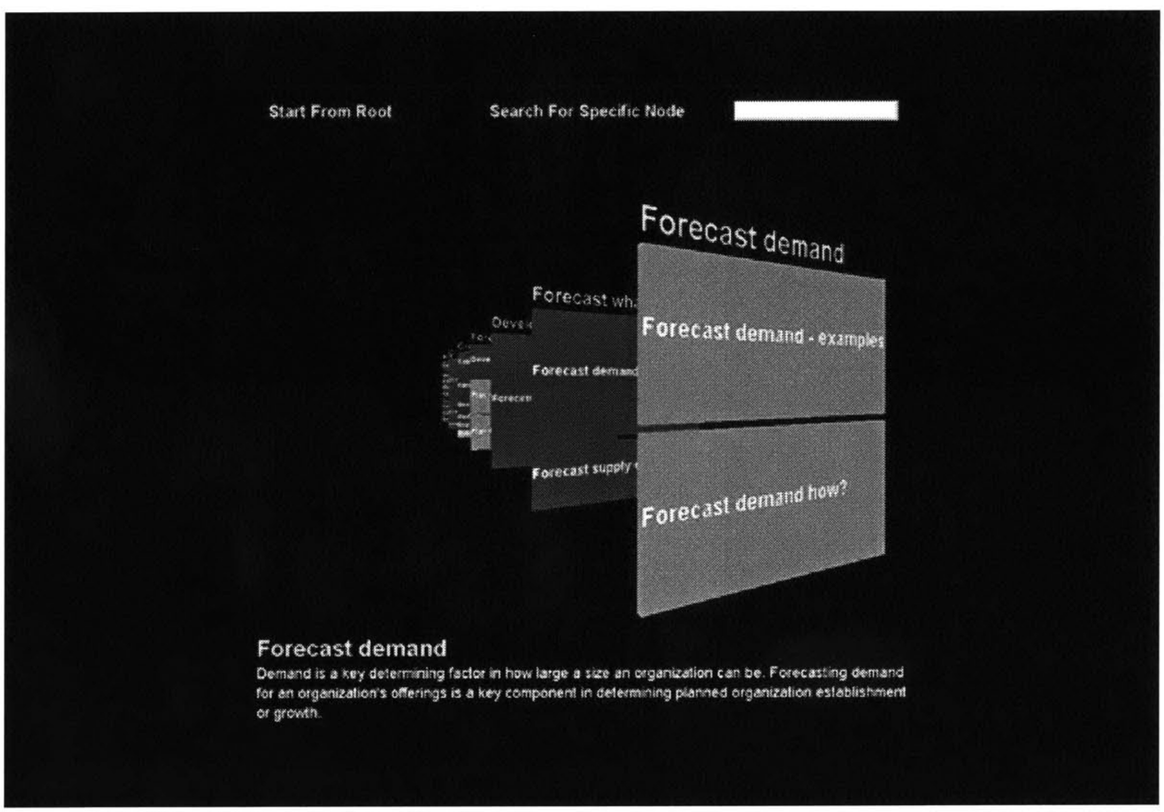


Illustration of the uncompress process.

When these screens are laid out along z-axis and with a convenient way to revisit each ancestor node, we can uncompress one screen to nine screens. In this way each node is assigned a reasonable display space. At the same time we can view its position in the hierarchy from its position along z-axis.



Screenshot of the 3D Tree-map application.

The user interface was developed in Java3D, the connection to database was written with JDBC API.

Chapter 4 Theory

After experimented with the two projects presented in last chapter, I want to find out the reason under the phenomenon revealed from them in order to address the problem from a more pertinent point. With three questions in mind, I studied mainly from two related areas. The three questions are:
What is the concept and cognition of space?
What is abstract thought?
What is the role of visuospatial cognition in abstract thinking?
The two areas are:
Cognitive science.
History, philosophy, and art.

There is no universally agreed definition or answer for any of these three questions, and there is no strict division for studies of these three subjects. Some materials about the role of spatial cognition in abstract thinking also describe the nature and property of spatial cognition under a more specific context.

What is the concept and cognition of space?

The spatial concept I want to focus on is on architectural (architectonic) scale and from real world (everyday) context. It is not a general definition of space from philosophical, physical, and mathematical meaning. It is about the three dimensional environment we have experienced since we were born. My research is about how we visualize the space, how we interact with it, and its effect on human cognition.

In general sense space is a concept which could evoke different ideas among people of different disciplines. For some, it is matter filled in between a pair of poles. For some, it is strictly geometrically defined area, accompanied with such epithet as "Euclidean", "isotropic", or "infinite". For architects, space is the permanent subject of design, what it evokes is the sequences of experience comes from partition, light, material, furniture etc. The last one may be most close to what is intuitively evoked in people's mind. For example, when talking about space, maybe, what comes into the mind of an old lady is the living room she is sitting in and the yard she is looking out from the window. The reason I chose to start from the concrete world is because this is what we perceive. Even though at certain stage we could conceive abstract space based on our knowledge of the concrete world, no one has ever seen the abstract space of points, lines and planes.

In the last three decades, there has been increasing interest in the research of spatial vision, spatial cognition, and visuospatial processing. There has also been great increase in our understanding of the nature and process of them. Through empirical demonstrations, theory proposals, and computational models, research on these topics have reached a new degree of explicitness and sophistication. Since human visuospatial cognition is a complex topic with many natures which could not be explained with enough evidence at present, there has been debates on many specific issues. But disagreement and lack of resolution surrounds many of them. Here I review only some generally accepted theories regarding the enssential parts in spatial cognition.

In the process of experiencing space there are two stages: visuospatial perception and visuospatial imagery. In the perception stage, we visually (through perception systems) pick up information from the environment on the visual properties of objects, spatial relations among them, and their motions within the environment. In the imagery stage, we mentally represent and process visuospatial information in a more constructive and less data driven way than that permitted in the visual system. "Through the retrieval of visuospatial information from memory, we are able to 're-experience' or reconsider past perceptual experiences and environments. Through the construction of mental representations, we can mentally combine visuospatial elements in new ways, perform or simulate mental transformations on them, and engage in reasoning and problem solving involving visual and spatial information." (Vega & Marschark, 1996)

Spatial Vision

We consider spatial vision mainly related to the process in which we get visual perception of the three-dimensional world. It derives from an on-line exteroception system that extracts information from images of external world activated on the retina. Perceptual images of spatial scenes are thus constructed in a bottom-up fashion in terms of edges, surface textures, and shadows.

Hall (1966) discussed the crucial role of spatial vision in the process human evolution. "The tactile, or touch, systems are as old as life itself; indeed, the ability to respond to stimuli is one of the basic criteria of life. Sight was the last and most specialized sense to be developed in man. Vision became more important and olfaction less essential when man's ancestors left the ground and took to the trees," "Stereoscopic vision is essential in arboreal life. Without it, jumping from branch to branch becomes very precarious." Newcombe et al. (2000) also point out the importance of spatial vision in terms of human adaptation. Anything concretely existing in the world must have a spatial location, it is vital for the survival and reproduction of human species to perceive and organize their actions in the spatial world.

In "Perception of the Visual World", Gibson focuses on this part of the spatial cognition - visual perception of space. The essential question in Gibson's study is: how do we see the world around us?

It is a common knowledge that there are a number of conditions must be fulfilled before one can see: there must be a light to see by, the eyes must be open, the eyes must focus and point properly, the sensitive film at the rear of each eyeball must react to light, and the optic nervous must transmit impulse to the brain. But it had been a problem which puzzled men for centuries of years, how can we perceive the space has depth, distance, and solidity? The physical environment has three dimensions; it is projected by light on a sensitive surface of two dimensions; it is perceived nevertheless in three dimensions. How can the lost third dimension be restored in perception? The visual world which extended in distance and modeled in depth is upright, stable, and without boundaries. It is colored, shadowed, illuminated, and textured. It is composed of surfaces, edges, shapes, and interspaces. It is also filled with things with meanings. How do we experience such a concrete visual world?

Different from what the "air theory" suggested that visual space, unlike abstract geometrical space, is perceived only by virtue of what fills it, Gibson proposed a "ground theory". The essence of that theory is that visual space should be conceived not as an object or an array of objects in air but as a continuous surface or an array of adjoining surfaces. The spatial character of the visual world is given not by the objects in it but by the background of the objects.

To make a better explanation of facts which cannot be explained by theories in the history, Gibson proposed two kinds of seeing, the experience of a visual world in which objects stay the same size wherever they are and parallel edges do not converge, and the experience of a visual field in which the principles of perspective hold true. Visual field has boundaries, whereas visual world is boundless. Visual field is sharp, clear, and fully detailed at the center, but progressively vaguer and less detailed towards its boundaries. Objects and surfaces composing the visual world are always clear and fully detailed. The visual field shifts whenever the eyes are moved from one fixation point to another. But the visual world is stable, it does not rotate as you turn around nor does it shoot from side to side or up and down as you shift your fixation from one object to another. The visual field always seems a little illusory. There is always the sense that one can bring back the world whenever one wished. There can surely be agreement that the visual world is marvelously well adapted to be the conscious accompaniment of behavior, while the field is not. If we adjusted our actions to some of the peculiarities of the visual field, we should go badly astray; thus when, because of fog or darkness, the environment is not seen as a visual world but only as some kind of a vague field, we proceed cautiously.

Gibson holds that both seeings depend upon light stimulation and upon a properly functioning eye. The great difference between them is caused by the difference between their generation processes. The visual field can only be observed with special effort, one gets it only by trying to see the visual world in perspective and to see its colors like a painter does. The observation of the visual world, on the contrary, is so natural that everyone takes it for granted, and never even think about its formation. But actually how all the characters of the seeing of visual world come into being is because it is observed by scanning, that is by moving the eyes rapidly from point to point. Through the experimental studies of main factors for the perception of the visual world, Gibson accounted the formation of both the pictorial seeing and objective seeing as a process accomplished through visual stimuli. To Gibson, the seeing of the visual world does not require a process of construction, translation, or even organization as an explanation. "The visual world can be analyzed into impressions which are object-like, and these impressions are traceable to stimulation. The fundamental impressions obtained by introspection are not colored bits of extensity but variables like contour, surface, slant, corner, motion, distance, and depth, in addition to color, all of which correspond to the variables of the distribution of focused light. These impressions do not require any putting together since the togetherness exists on the retina. The suggestion is that, philosophers and estheticians to the contrary, order exists in stimulation as well as in experience. Order is just as much physical as mental." (Gibson, 1950)

Mental Representation of Space

By contrast with spatial vision, the mental representation of space derives from the top-down (conceptually based) retrieval, or generation of virtual images that are used in the context of explicit or implicit task demands.

Pinker (1988) borrowed Gibson's concept of dividing the spatial perception as "visual field" and "visual world". But his research is trying to prove that the construction of the visual world involves mental imagery process. He considers spatial perception as a cognitive process. From his point of view, the world reveals itself to us as a two-dimensional pattern on our retinas. Our brains somehow use these perspective effects to build an internal representation of the three-dimensional world. In that representation, things parallel keep parallel, and objects in general have rigid 3D shapes and intrinsic size and occupy fixed locations in a stable three-dimensional framework. He took the railroad tracks as example, the seeing of the tracks converge in the visual field, remain parallel in the visual world. "Real railroad tracks reflect light rays in such a way that converging lines are projected onto our retinas. But mental representations of railroad tracks do not reflect light rays, and the mind's eye surly has no lens or retinas to focus them even if they did. Rather the internal representation of the tracks must be accessed directly by the cognitive processes that interpret mental images, and therefore the tracks should be experienced as parallel in images."

"As a first step toward understanding the mental representation of space, we might ask whether a mental image represents information as it appears in the visual field, which characterizes the early stages of visual processing, or as it appears in the visual world, which is an achievement of the higher cortical systems which interface with more abstract thought processes." He came to the conclusion that there are four facts accounted for the mechanisms underlying mental imagery for three-dimensional scenes. "First, images preserve information about the three-dimensional structure of the visual world. Second, images preserve the two-dimensional perspective view of the visual field. Third, images can display new perspective views of a scene as it would appear from a novel viewing angles. Fourth, imagined objects can be rotated or translated in three-dimensions in a smooth, continuous fashion." Pinker thinks there should a process that can construct a perspective view of the 3D world based on information of the 2D appearance in the visual field and information of the 3D structure in the visual world stored in the memory. The process can generate a scene according to its 3D description and specification of a viewing angle and distance, and a set of transformation processes that alter portions of the imagined scene.

Spatial Schemas

Aside from visuospatial perception and visuospatial imagery, some researchers suggest another stage, visuopatial conceptual stage, staying in between. They believe that the information from the perceptual level is "digitalized" into a few topological categories at this stage. For example, the image-schema of containment allows the building of a more abstract categorization of "inside" and "outside" regions in containers; the support schema allows us to distinguish "above" area from "below" area; and the body schema permits us to categorize the "front", "back", "right", and "left" into intrinsic frameworks. The spatial meaning is considerably simplified on this middle stage. The sensorium information is transformed into a mental model of the world at a distance. The spatial cognition of this stage delivers a three-dimensional model of the world, which is inferred through the visualspatial perception from the pattern of light intensities falling on the retinas.

Kosslyn (1992) proposed two subsystems in identifying unfamiliar shapes: the coordinate property lookup and the categorical property lookup. The role of categorical property lookup and the categorical spatial relations encoding, which deal with the abstract spatial relations, are quite similar to that of the conceptual stage. "In considering what kind of properties remain the same as we take photographs of a person knelling, standing, walking, rolling over, and so on, we notices that no parts are added or deleted (although some parts are occluded in some postures). In addition, notice that the spatial relations among the parts remain the same, if we characterize the relations at a rather abstract level of analysis. For example, the forearm remains 'connected to' the upper arm, no matter how the person twists and turns, and the ears remain on the 'sides of' the head, and so forth. Categories such as 'connected to', 'above', 'inside', and so on are abstract because they group over a wide range of variation; they treat positions that share a single attribute of the spatial relation as equivalent."

The term "literal perception" and "schematic perception" in "The Perception of the Visual World" could be considered as corresponding to the perception stage and the conceptual stage respectively. Schematic perception is more intricate than literal perception. According to Gibson (1950), the perception of everyday life is often schematic. The schematic perception could be fluid, subjective, creative, and inexact. It is the percept reduced to a cue for action. In the schematic world of cues and signs, many of the qualities of color and space are dropped away. "But perception can become literal whenever the observer needs to discriminate." "In the thinking of many artists, for example, there exists a confusion between the seeing of space and the seeing of symbols. They are not clear where the difference lies between representing and symbolizing."

There are echoes of the theory of visuospatial conceptual stage from philosophical, psychological, and visual arts studies, which help us reach a more comprehensive understanding of spatial cognition process.

Some philosophers hold the point of view that spatial perception is not the perception of space as such but of the relationship between objects in space. Plato stated, "The lowest form of thinking is the bare recognition of the object. The highest, the comprehensive intuition of the man who sees all things are part of a system."

To analyze how perspective opens art to the realm of psychological sense, Panofsky(1991) highlights the role of abstract spatial structures in the evolution from "aggregate space" to modern "systematic space" in art. "Exact perspectival construction is a systematic abstraction from the structure of this psychophysiological space. For it is not only the effect of perspectival construction, but indeed its intended purpose, to realize in the representation of space precisely that homogeneity and boundleness foreign to the direct experience of that space." Before Renaissance, painting concerned itself with isolated objects. The space seems to be a consumption of objects, a simple superposition, and unsystematic overlapping. There was no attempt to represent the space between objects and failed to reveal the relationship between them. The extensive involvement of abstraction from the psychophysiological structure of space in Renaissance makes it possible to "construct an unambiguous and consistent spatial structure of infinite extension, where body and the intervals of empty space between them were emerged in a regular fashion into a *corpus generaliter sumptum*('body taken in a general sense')." By such a definition, space is conceived and represented as "a system of simple relationships between height, width and depth. In that case, in the guise of a 'coordinate system,' the difference between 'front' and 'back,' 'here' and 'there,' 'body' and 'nonbody' would have resolved into the higher and more abstract concept of three-dimensional extension, or even, as Arnold Geulincx puts it, the concept of a *'corpus generaliter sumptum'*."

In "Thinking visually", McKim's (1980) concept of "mind's eye" illustrated the conceptual stage of spatial cognition too. "The mind's eye, spontaneously active in dreaming, can also be consciously directed. Unlike the sensory eye, which is bound to the here-and-now, the mind's eye can travel in space and time to the there-and-then, can entertain fantasy, can form, probe, and manipulate structures and abstract ideas, can obtain insight into realities that have not yet been seen and can foresee future consequences of present plans."

What is abstract thought?

In "Learnability and Cognition", Pinker (1989) cited two views on this subject. "Chomsky terms the evolution of abstract cognition a 'mystery'. Fodor suggests that abstract thought processes are so unconstrained that one can't even characterize them in an interesting scientific theory."

We could view abstract thought as one of the following cognitive actions: conceiving, discriminating, analyzing, synthesizing, interpreting, anticipating, comprehending, composing, imagining, remembering, and expressing ourselves without or without words.

From information processing point of view, we could think abstract thought as retrieving, storing, manipulating, understanding large amounts of information, and assessing change, dynamics, and cause and effect. It also related to discovery, decision-making, explanation, and see phenomena in the data.

In a more general term, we could consider abstract thought as memory, reasoning, communication and language comprehension.

What is the role of visuospatial cognition in abstract thinking process?

As human beings, our reality is a three dimensional world. Visuospatial cognition is perhaps our most important form of information processing. It appears that abstract thinking is built on representations of experience-based domains; abstract knowledge is built analogically from experience-based knowledge. One's understanding of the abstract domain of time, for example, is intimately dependent on the experience-based domain of space.

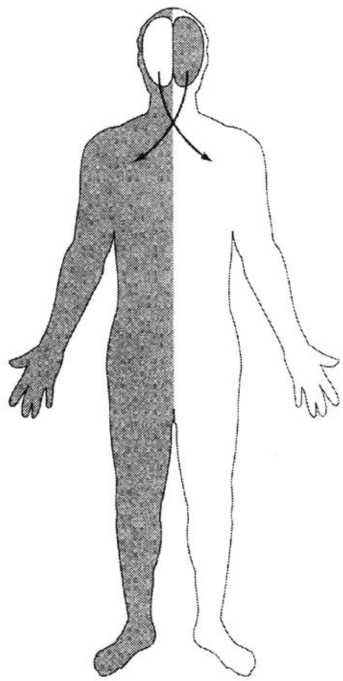
Even though pioneers of artificial intelligence who come from mathematical background firmly believe that all reasoning is logic, man does not reason only logically. In fact, under many circumstances, logical reasoning is the last way we choose, and visuospatial process plays an important role in the reasoning, problem solving, and creativity. For example, visuospatial process plays a vital part in language comprehension in dealing with both abstract and concrete materials. We use our "mind's eye" to rotate, fold, travel, and even zoom in and out on visuospatial images for discovery of novel patterns. For over two millennia, visuospatial strategies have been used to augment human memory. They also have played prominent roles in science as well as in art.

"Perception is the transformation of local information at sensorium into a mental model of the world at a distance, thinking is the manipulation of such models, and action is guided by its results"(Johnson-Laird). According to Panofsky (1991), spatial perception could be the base for art and science. The perceptual space is visually symbolized to be the "aesthetic space". When appearing in logical form, the perceptual space is recast to be the "theoretical space", which is a translation from psychophysiological space into mathematical space, an objectification of the subjective.

To Plato, memory and thought appeared to progress from innate abstraction to language to image. To Aristotle, however, thought never occurred without a mental image. The abstraction in thought is constructed by means of organizing sets of images according to concrete spatial experience. "All men can think because it is possible to put things before our eyes, the way those who invent trained memory techniques teach us to construct images."

In this section I will present related studies from four subtopics: how perception play its role in abstract cognition; what is mental imagery and its use in reasoning; what is the use of space in the art of memory; and how spatial schemas can be used in abstract thought.

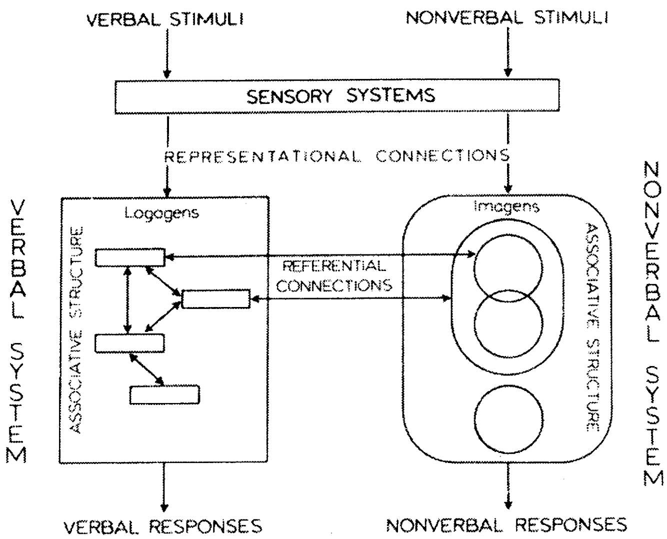
Body Asymmetry and Dual Coding



Body Asymmetry
From Craig Denton, *Graphics for Visual Communication* [Wm. C. Brown Publishers, 1992], 65.

The brains of all animals are divided into two hemispheres. However, only in humans the two hemispheres develop and function asymmetrically. The left side of the brain controls the right side of the body, and the right hemisphere directs the left side of the body. Beyond this, the two hemispheres also "think" differently. The left hemisphere is rational and analytical. It thinks "objectively" with symbols and abstract concepts. It naturally explores sequential, logical, cause-effect relationships. It seeks for reasons, facts, and quantities expressed in numbers. The right hemisphere is holistic and spatial, grouping information into wholes based on their relationships. Instead of plodding from one thing to another in a sequence, it sees everything simultaneously. It focuses on the way things are at the moment and appreciates the complexity of the parts that make up the whole. It is intuitive, where knowledge is revealed rather than deduced. The right hemisphere is the sensuous half of the brain, relishing the concrete and here-and-now; it is also "subjective", finding reality in metaphor and perceiving emotional nuances. The left hemisphere is the primary center for verbal expression; the right hemisphere is the primary center for comprehending spatial relationships. And thus the left hemisphere is also called verbal hemisphere, while the right is called the spatial hemisphere.

Based on the neuropsychological literature of hemisphere asymmetry, Paivio (1986) explored the cognitive functions of visuospatial imagery in verbal learning paradigms, and formulated a dual coding model for memory and cognition. That theory distinguishes two independent but interconnected symbolic processing systems, a verbal system and a nonverbal or imagery system. The verbal system is specialized in dealing with relatively abstract information, such as language, whereas the specialization of the imagery system is processing concrete-perceptual information, such as nonverbal objects or events. Parallel to the verbal and imagery system in long-term memory, Baddelry suggested that working memory also involves a central execution aided by at least two subsidiary systems, an articulatory loop involved in storage and processing of verbal material, and a visuospatial sketchpad that performs a similar function for visuospatial material.



Schematic depiction of the structure of verbal and nonverbal symbolic systems.
From Allan Paivio, *Mental representation: A dual coding approach* [New York: Oxford University Press, 1986]

A basic premise of dual coding theory is that mental representations retain some of the concrete qualities of external experiences from which they are derived. Its basic concept can be revealed through the interpretation of two findings for visuospatial imagery.

Concrete effect

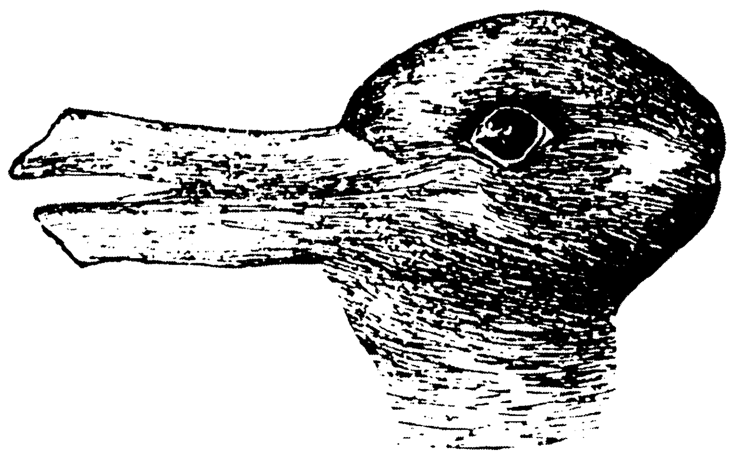
Concrete words, such as words that refer to concrete referents, are generally easier to remember than abstract words. Interpreted from the dual coding model, this result derives from the fact that concrete words are more likely than abstract words to evoke mental imagery. Concrete words are thus encoded in both verbal and imaginal system, whereas abstract words are more likely to be encoded only in the verbal system. These two systems are seen to be separate but interconnected such that at the time of retrieval "two codes are better than one."

Imagery effect

Instructions to use imagery improve memory for verbal materials as compared to standard memory instructions that do not entail mental imagery. The dual coding explanation is that imagery instructions increase the likelihood of dual verbal and imaginal encoding in long-term memory relative to standard instructions.

Traditionally, thinking has been considered a symbolic activity quite separate from seeing. According to this view, seeing is sensory information-gathering; the higher mental activity for thinking is verbal or mathematical information-processing. One merit of dual coding model is that it raises the attention for research on the role of concrete perceptual process in abstract cognition. Under the general frame of dual-coding theory, there is research in Paivio's lab concentrated specifically on the importance of spatial cognition in accomplishing abstract tasks.

Back to the consideration of the asymmetry of body and brain; look at the following figure:



From Robert McKim, *Thinking Visually* [Lifetime Learning Publications, Wadsworth, Inc., 1980], 24.

When experiencing the image of a "duck" or a "rabbit" alternatively, you are actually moving your thinking from one hemisphere to another. Even though there is the term "hemispheric preferences", it is possible to make them work together. Creative people in every field are ambidextrous in their thinking. Some of the most famous discoveries in science were made when possible events being visualized and their outcomes being "observed". "For example, Albert Einstein claimed that he had his first insight into the theory of relativity when he considered what he 'saw' when he imaged chasing after and matching the speed of a beam of light. He notice that if light were a wave, he should see a particular pattern when he paralleled its flight". "Einstein used imagery as a way of reasoning, mentally setting up possible scenarios and 'observing' what would happen if nature worked that way." (Kosslyn, 1992)

Visuospatial thinking complements to abstract-language thinking with its power to make things concrete. These two thinkings are also complementary by virtue of differences in structure. "Verbal and mathematical symbols are strung together linearly in conventional patterns such as those afforded by grammar. Mentally tracking these linear structures automatically enforces certain thinking operations. As if fingering beads, the thinker follows the verbal or mathematical pattern piece by piece, toward a single end. Visual imagery, by contrast, is holistic, spatial, and instantly capable of all sorts of unconventional transformations and juxtapositions." (Mckim, 1980) Our thinking ability will thus become more powerful when we make our left and right brain work together.

Mental Imagery and the Visual World, Reasoning Using Imagery

"'Mental imagery' is defined as the mental invention or recreation of an experience that in at least some respects resemble the experience of actually perceiving an object or an event, either in conjunction with, or in the absence of, direct sensory stimulation." (Ronald, 1989)

Mental imagery is mental representation of the three dimensional visual world. As one stage of spatial cognition, its relationship with the thinking process is very important for the study of spatial cognition and thought. "The subject of imagery is tied to scientific and literacy creativity, mathematical insight, and the relation between cognition and emotion; though the scientific study of imagery is mostly concerned with more pedestrian spatial abilities such as memory for literal appearance, spatial transformations, and matching images against visual stimuli, it has been argued that an understanding of these abilities may give us the toehold we need to approach the less tractable topics in the future." (Pinker, 1985)

The concrete world being represented by imagery could be imaged as detailed, or as schematic, generic structure. In either case, imagery attains a high degree of structural isomorphism with the objects they stand for. Imagery can be used to metaphorically represent non-spatial relations or processes, such as the comparative judgments or transitive inference. Imagery can also be implemented, with additional cognitive effort, to mentally picture highly abstract information.

Thinking can be thought of as a set of mental activities involved in the manipulation of representational information with, as outputs, the construction of new pieces of information which can enter into an individual's knowledge base. Imagery is beneficial in thinking in that it preserves the intrinsic structural coherence of the objects or configurations they reflect. Its structural and processing properties make it a medium for the manipulation of information in a constructive manner, which are vital for the thinking processes such as predictive reasoning, comparative judgment, productive thinking, and spatial reasoning. It allows subjects to avoid the mechanical use of algorithms elicited by the verbal formulation of the problem. (Shepard, 1978)

Imagery has been taken into consideration in the theory of thinking which positing the essential role of prepositional representations in thinking. It is also considered in theory for the spatial-analog hypothesis, which argues for the functional significance of visuo-spatial representations in syllogistic reasoning. Other research show that mental imagery plays key roles in the higher cognitive functions of mental representation, creative thinking, and planning complex actions. It offers critical support to a variety of thinking processes, including spatial reasoning, problem solving using analogical representations, or mental discovery of novel or emergent properties.

There are two extreme views concerning the role of imagery in thinking. First, imagery is the essence of thinking, and thinking is the generation and manipulation of images. Second, thinking involves the manipulation of abstract representational entities, which have no counterpart in the concrete representations furnished by mental imagery. Thinking is too abstract a process to develop alongside the certain side effects associated with the generation of concrete visual images. One compromised view is that imagery is a set of processes which have their own properties, and can be brought into play at various levels of cognitive activity. It is not the core of thought processes, but rather a potential medium for them. Thinking makes use of representations, some of which are produced by imagery processes, and some by more abstract representational systems. Images, then, are reality models for thinking.

In the following paragraphs I will list many properties of mental images which are relevant to thought process.

Mental images have the structural similarity to perceptual representations. Objects and events are represented in an analogical format, so that it is possible to mentally anticipate transformations of the external world. "The processing of many sorts of problems has been shown to be facilitated by the construction and exploration of representations with a figural content."

Mental images are economical considering of memory load. "Images are mental representations which have been termed economical, in that the elements making up an image are organized into highly integrated structures. By contrast with enumerative list of object properties, image maintains a large number of information units together as a unified whole. This integrative feature of images may minimize memory load. The efficiency of imagery in learning and memory may be due to additional coding of information made possible through imagery, but also to the integrative character of the products of this coding, which reduces possible interference effects. Imagery can thus be seen as a process which increases the availability and manipulability of information currently processed in working memory." (Cornoldi & McDaniel, 1991)

Mental images may provide a simplified representation of the content of the cognitive task. For instance, schematic images highlight the salient elements of a given situation allowing such elements to be processed easily and rapidly.

Mental images are flexible representations which permit the manipulation of problem elements in unusual ways. The flexible and rapid manner in the manipulation also enables on-line inspection of current hypothesis.

Mental images are holistic representations specialized for parallel processing of information, so that they facilitate simultaneous consideration of the whole problem fields and mitigate the tendency to examine single elements sequentially.

Mental images may help subjects restructure the problem because they imply dynamic transformations of the given material.

In the thinking process, imagery can be used either denotatively or symbolically. It has been argued that visual imagery can play a simulation and a symbolizing function in thinking (Kosslyn, 1983). When the problem statement describes physical objects and the physical operations to be performed on them, images are cognitive reflections of a real world. They are essentially denotative. For problems which cannot be directly pictured, imagery is used for its symbolic value, and it is a notation in this case. It serves as a cognitive aid in the development of abstract reasoning or thinking. It translates non-spatial information in the form of spatial metaphors. (Denis, 1988)

We use imagery to access stored information of an object by generating an image and then inspecting the imaged object for the sought information through scanning, zooming, or transforming. The maintenance and transformation of visual images normally occur as part of some other cognitive process. Its transformability and flexibility make it helpful for creative processes that cannot be done using words alone, such as creative design, scientific reasoning, or general problem solving. In mental synthesis, discrete parts in an image are transformed and manipulated in order to form novel patterns or to allow novel insights. The technique of "combinatory play" advocated by Einstein is an often-cited example of such mental synthesis. Discoveries based on image transformation has also been attributed to Kekule, Faraday, and Feynaman among others.

The Art of Memory

Cicero, like many other orators of his time, was able to make long speeches without notes by roaming through a space constructed in his mind to call up ideas he wish to discuss which were located to rooms and furnishings in that space. In his artificial memory, Cicero "moved among the buildings of ancient Rome, seeing the places, seeing the images stored on the places, with a piercing inner vision which immediately brought to his lips the thoughts and words of his speech." Yates uses the expression "the art of memory" to define this impressive process.

Invented by Simonides, the art of memory is an art seeking to memorize through a technique of impressing "place" and "images" on memory, in a way like an inner writing. "The places are very much like wax tablets or papyrus, the images like the letters, the arrangement and disposition of the images like the script, and the delivery is like the reading." (Yates, 1966)

In his "On the Orator", Cicero first told the vivid story of the invention of the art of memory. Scopas, a winner of a boxing contest, commissioned Simonides to write an ode in his honor and chanted on the victory banquet. When he learned that Simonides had devoted half of the poem to Castor and Pollus, the divine twins famed for their boxing skills, he meanly told the poet that he would only pay half the agreed sum and that he must obtain the rest from the two gods. A little later, a message was brought in to Simonides that two young men were waiting outside who wished to see him. He rose from the banquet and went out but could find no one:

> ...but in the interval of his absence the roof of the hall where Scopas was giving the banquet fell in, crushing Scopas himself and his relations underneath the ruins and killing them; and when their friends wanted to bury them but were altogether unable to know them apart as they had been completely crushed, the story goes that Simonides was enabled by his recollection of the place [*loco*] in which each of them had been reclining at table to identify them for separate interment; and that prompted then by this circumstance he is said to have invented the order that especially brings light to memory. And so for those who would train this part of the mind, places [*loci*] must be selected and those things [*rerum*] which they want to hold in memory must be reproduced in the mind and put in those places: thus it would be that the order of the places would preserve the order of the things; moreover, the likeness [*effigies*] of the things would represent the things themselves, and so we use places instead of a wax tablet, images instead of letters. (Cicero, *On the Orator*, 2.351-354)

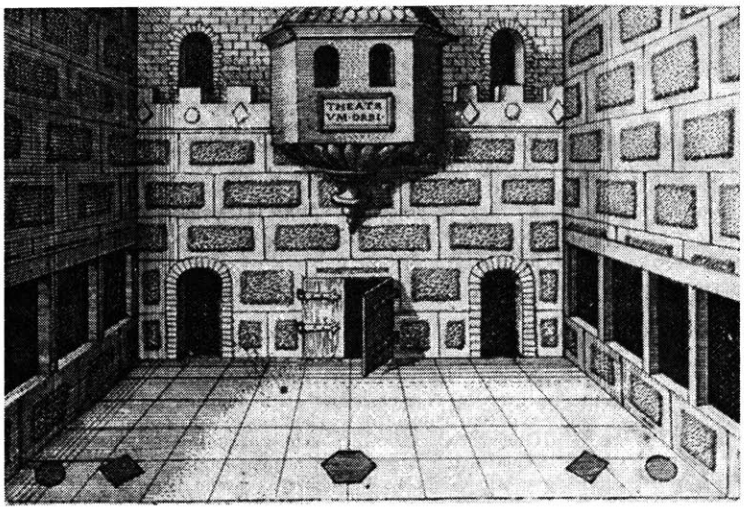
The two gods handsomely paid for their share in the poem by drawing Simonides away from the banquet just before the crash. And this experience suggested to the poet the general principles of the art of memory. "The first step was to imprint on the memory a series of loci or places. The commonest, though not the only, type of mnemonic place system used was the architectural type." "In order to form a series of places in memory, a building is to be remembered, as spacious and varied a one as possible, the forecourt, the living room, bedrooms, and parlours, not omitting statues and other ornaments with which the rooms are decorated. The images by which the speech is to be remembered are then placed in imagination on the places which have been memorized in the building. This done, as soon as the memory of the facts requires to be revived, all these places are visited in turn and the various deposits demanded of their custodians."

"The formation of the loci is of the greatest importance, for the same set of loci can be used again and again for remembering different materials." "A locus is a place easily grasped by the memory, such as a house, an intercolumnar space, a corner, an arch, or the like." "If we wish to remember much material we must equip ourselves with a large number of places. It is essential that the places should form a series and must be remembered in their order, so that we can start from any locus in the series and move either backwards or forwards from it." "Memory loci should not be too much like one another. They should be of the moderate size, not too large for this renders the images placed on them vague, and not too small for then an arrangement of images will be overcrowded. They must not be too brightly lighted for then the images placed on them will glitter and dazzle; nor must they be too dark or the shadows will obscure the images. The intervals between the loci should be of moderate extent, perhaps about thirty feet, 'for like the external eye, so the inner eye of thought is less powerful when you have moved the object of sight too near or too far away'." (Yates, 1966) The places can be either real buildings or fictitious imaginary buildings. The places can be either "natural places" which are memorized in the country as trees in the fields, or "artificial places" which are memorized in buildings, as a study, a window, a coffer, and the like.

More than one century after Cicero's *On the Orator,* Quintilian, a dominating teacher of rhetoric in Rome, proposed his "simpler percept" of memory training, namely to learn a passage by heart from the same tablets on which he has committed it to writing. "For he will have certain tracks to guide him in pursuit of memory, and the mind's eye will be fixed not merely on the pages on which the words were written, but on individual lines, and at times he will speak as though he were reading aloud...." This method adopts the habit of visualizing writing on "places" from the mnemonic system. Instead of attempting to visualize shorthand note on some vast place systems it visualizes ordinary writing as actually placed on a tablet or page.

As the last great monument of Renaissance memory, Fludd's memory system takes a theater as its architecture form, which comes from the depiction of the "real place" of "Public theatre". He poetically metaphorizes the system as "a theatre (a place in which) all actions of words, of sentences, of particulars of a speech or of subjects are shown, as in a public theatre in which comedies and tragedies are acted."

As shown in the following figure, what he means by "theatre" is actually a stage but not a building consisting of a stage and an auditorium. The wall facing us contains five entrances. It is a multilevel stage. Three of the entrances are on the ground level; two are arches, but the central one can be closed by heavy hinged doors which are shown half open. The other two entrances are on the upper level; they open on to a battlemented terrace. In the center, there is a kind of bay window, or an upper chamber or room. There are five columns opposite to the five doors, the bases of which are shown in the foreground of the picture. The shapes of the two at extremity are round, the central one is hexagonal, and the intermediary ones are square. These columns are of different colors corresponding to the doors they opposite to, the colors of which are, the first white, the second red, the third green, the forth blue, and the fifth black.



The Theatre
From Robert Fludd, Ars memoriae (pp. 330ff., 346 ff.)

In all the rules for places, the sense of space, depth are suggested. And early as Cicero's time, in the development of the art of memory, people realized the importance of the sense of sight in the construction of the ordered space in the mind. They find that the sense of sight is the strongest among all the senses, and the mental process in the training involves visuospatial perception of high intensity. "It has been sagaciously discerned by Simonides or else discovered by some other person, that the most complete pictures are formed in our minds of the things that have been conveyed to them and imprinted on them by the sense, but that the keenest of all our senses is the sense of sight, and that consequently perceptions received by ears or by reflexion can be most easily retained if they are also conveyed to our minds by the mediation of the eyes."

Those ancient insights are consistent with result of current research on the role of spatial cognition in memory and thought. Through its successful practice the loci method proves that spatial perception is powerful and helpful to memory and thought. The perception of space collects and provides traces to set up the space in mind. The spatial structure acquired from the conceptualization of the space provides the structure for memory materials to map to.

There is a strong association between the art of memory and the art of thinking. Even though we think of memory primarily as a retrieving process, in ancient time memory was considered to be more active. It was intimately connected to thinking. Thinking, writes Sir Frederick Bartlett, is the utilization of the past in the solution of difficulties set by the present. Philo Judaeus, a philosopher who lived during the early Roman Empire, linked memory to God and creation in a passage in "On the creation". It is stated in a way quite like the artificial memory systems. "When a city is being founded...there comes forward now and again some trained architect who...first sketches in his own mind well nigh all the parts of the city that is to be wrought out, temples, gymnasia, town-halls, market-places, harbors, [ect.].... Thus after having received in his own soul, as it were in wax, the figures of these objects severally, he carries about the image of a city which is the creation of his mind. Then by his innate power of memory, he recalls the images of the various parts of this city, and imprints their types yet more distinctly in it.... Just such must be our thoughts about God.... As, then, the city which was fashioned beforehand within the mind of the architect held no place in the outer world, but had been engraved in the soul of the artificer as by a seal; even so the universe that consisted of ideas would have no other location than the Divine Reason, which was the Author of this ordered frame." (Philo Judaeus, *On the Creation*, 17-20.)

In the later part of "the art of memory" Yates studied the transformation of the art of memory from a method of memorizing knowledge and reflecting the world in memory to an aid for investigating the world with the object of discovering new knowledge. In "Logic and the art of memory", Rossi (1983) further pointed out the vital role the art of memory played in the rise of early modern science and logic, whose objective was to "enable man to see beyond the veil of phenomena appearances, or the 'shadow of ideas', and grasp the ideal and essential structure of reality", "discovering the correspondence between the original forms of the universe and the structure of human thought." Many thinkers had also addressed themselves to the problem of topica and artificial memory, stressing the function of loci as a means of delimiting and ordering fields of research. Melanchthon, for example, said that loci "teach us where to look for the matter we are seeking, and how to select things from a great mass of material. The loci of invention, whether in dialectics or rhetoric, do not direct us towards the matter one needs, but teach us how to select the matter from the information one has already accumulated." Bruno uses hundred and thirty fundamental memory places, which are essential components for artificial memory, as the basic elements of a system of logical relations. Ong, in his "Ramus, Methods, and the Decay if Dialogue", elaborated the role of "spatialization" of mental constructions in the development of method and logic in the late sixteen century.

Spatial Schemas and Abstract Thought

In the end of "Learnability and Cognition", Pinker(1989) discussed "spatial schemas and abstract thought" as a potential topic for future research. Recently, Gattis (2001) brought together research on this topic from multiple disciplines as a book under the same title.

Pinker (1989), Lakoff and Johnson (1980) all proposed the concept that our experience in space and the cognitive structure we developed to perceive, navigate, and remember space are the indispensable foundation of more abstract cognitive tasks. Spatial schemas which "represent the locations and paths of movable objects may have been co-opted in hominid evolution to represent abstract states and changes." (Pinker, 1985)

As a stage of spatial cognition schematized from the direct spatial perception, spatial schemas has more features beneficial to the abstract thought than the other two stages. Schematization is a process that reduces a spatial vision from a real physical world, with all its richness of details, to a sparse and sketchy semantic content, which has the facets of systematic selection, idealization, approximation, and conceptualization. This reduction involves abstracting objects as simple geometry entities: points, lines, and surfaces, and analyzing these entities as part of a relational structure. For expressions such as " The village is on the way to London", the "village" is a point lying on the line connecting the present location and the point representing "London".

Spatial schemas are acquired in a purely spatial context. To be used for abstract cognition tasks, they must be adapted to the abstract structures, such as memorial structures, communicative structures, or logical structures. The use of spatial schemas as an organization of objects in the space to facilitate memory has been discussed in the above section of the art of memory. In communication, spatial schemas can be used to represent the opposition between two entities, to identify categories and directionality. The property of spatial schemas which is beneficial to logical reasoning is that it provides a possibility of inferring new elements or relations from the existent structure. "Spatial schemas do so by marking three aspects of structure that play a significant role in logical reasoning: order within a dimension, directionality within a dimension, and relations between dimensions." (Gattis, 2001)

Spatial schemas can provide models of actual and theoretical worlds, convey meanings, facilitate discovery and inference. Likely uses of space are to encode time, number, order, location, and motion, plot progression, and paradigmatic contrast. Spatial arrays can be used to represent non-spatial information based on proximity from nominal and ordinal to interval and ratio.

Spatial schemas play an important role in reasoning, particularly in temporal reasoning and relational reasoning.

Analog time to space is a very common phenomenon in language. Time is often talked about in terms of space. Time consuming is often referred in terms of spatial motion. In language, there is a systematic mapping between time and space, the framework provided by which often facilitate temporal reasoning. This is because our representation of space, a concrete domain, is much more coherent and well structured than of time, an abstract domain. There are also further relations imported beyond the initially parallel relationships between the two structures. This is consistent with the rules of typical analogical mapping. "An initial alignment between common relational structures invites the mapping of further inferences from the more systematic domain to the less systematic domain. Thus candidate inferences are projected from the highly structured domain of space to the more ephemeral domain of time." (Gattis, 2001)

Space is relational. Full of diversity and flexible relationships, spatial structures can be used to represent enormous variety of abstract structures and concepts. Relational reasoning is a reasoning based on or about the relations between elements, such as linear ordering and transitive inference. And thus it is the reasoning, more than other abstract tasks, benefited from adaptation of spatial structures.

Relational inferences are often arrived from the inference of the corresponding imaginal spatial relationships. For example, in the following deductive thinking: the book is on the left of the cup, the computer is between the book and the cup, therefore, the book is on the left of the computer, the inference may involves a schematized mental representation of the a scene depicted from the premises. Thus the result is "read" off from the scene as if actually seen from an array of objects. Johnson-Laird also proposes that "Indeed it may be that human inference in general is founded on the ability to construct spatial, or quasi-spatial models, which also appear to play a significant part in syllogistic reasoning and reasoning with multiple quantifiers"(Johnson-Laird and Byrne 1991).

Many of the spatial relations are transitive. Our visuospatial ability in computing spatial relations provides the basis of using spatial schemas reasoning on transitive relations. It is natural that routines of processing transitive spatial relations can be used in the reasoning process of non-visual transitive relations. To use visuospatial routines to transitive reasoning, there is a need for a mapping from linguistic statements of premises to spatial representations based on their pair-wise relations. The resulting value in forms of locations can then be used to compute additional relations, and the concrete inferences of specific objects can be mapped back to the abstract reasoning from the spatial relations.

The major stages of analogical thinking include "access (retrieving a useful source analog from long-term memory given a novel target problem or situation as a cue), mapping (discovering the correspondences among the elements of the source and the target), analogical inference (using the source to make inferences about the target), and schema induction (using the source and target together to induce a more general schema or rule)." (Gattis, 2001) Using spatial schemas in reasoning is one type of analogical thinkings. In this process, the mapping between spatial and non-spatial structure is important. Gentner proposes four possible levels of mapping: lexical relations, structural parallelism, cognitive archaeology, and system mapping. Based on related research, Gattis proposes that four constraints may affect the process of mapping concepts to spatial representations: iconicity, associations, polarity, and structural similarity. The similarity between abstract source and spatial representation for these four constraints are on different levels of abstraction.

Iconicity constrains the construction of spatial representations based on perceptual similarity or resemblance, by keeping some similarity of perceptual features or perceptual relations of what is represent. It is a selective constraint, only keeps the partial isomorphism important for relations being represented. The street map of a city and the underground transportation map of the same city can show how its selectivity facilitates the representation of specific sets of objects and relations between them.

Associations constrain mapping based on attribute or property similarity. Even though it also comes from perceptual experience, the perceptual process is only a bridge to reach the concept and attribute property of the objects and relations being represented. The rules of this constraint is acquired mainly from experience and learning, not from the direct perception of visual resemblance. The association of actions or events with specific locations and the using of "bigger" in spatial extent to represent "more" are examples for this constraint.

Polarity constraint is specifically for mapping relations of valence or directionality. It is based on the organizational structure underlying many perceptual and conceptual dimensions. It is realized by mapping the oppositional concept to directionality of spatial dimensions, in the way like a continuum with asymmetrically weighted ends. For example, when "good" and "bad" to represent two opposite concept, "goodness" is often used to refer to the whole dimension with "bad" as a specific end of the dimension. "bad" is understood by reference to "good" and is marked at different places on the whole dimension for different degrees of bad.

Structural constraint is based on similarity of relational structures, which leads to a pairing of elements to elements, relations to relations, and higher-order relations to higher-order relations. In the mapping process, relational structures at different levels are paired correspondingly. For example, "conceptual relations are mapped to spatial relations, such as height, and higher order conceptual relations are mapped to higher-order spatial relations, such as slope." (Gattis, 2001)

Summary

In summary, spatial cognition could help people in abstract thinking in three main aspects. Their features are listed in the following chart.

Aspects	Actions	Process or Properties of Spatial Cognition Involved
Memory	Associating	Storing information to locations. Organizing information spatially. Associative thinking
Inference	Manipulating	Manipulating representatives of abstract information like objects in space with spatial relationships. Constructing a scene depicted from the premises, with its result "read" off from the scene as if actually seen from an array of objects. Space is relational, full of diversity and flexible relationships. Our visuosptial ability in computing spatial relations provides the basis for using spatial schemas in relational reasoning. Analogical thinking
Discovery (of patterns, novel or emergent properties)	Observing	Spatial perception is holistic, proximate, and fuzzy. Synthesizing and comprehending massive amount of information quickly and easily. Detecting approximate and fuzzy relationships which are constrained by literal definition Imagining events happening spatially.

Chapter 5 Approach It with the Aid of Computation

Why

The loci method helps memory. But why is the loci method not being used any more? Has the cognitive value of space in the loci method disappeared? What constrains the use of space in thinking? How to take advantage of the strength of spatial cognition by overcoming these constraints to extend human cognition as a whole?

Two practical reasons account for the disappearance of the art of memory in modern time. First, massive information which previously could only be stored in memory is now available in varieties of formats such as books, internet, and database. Second, to use the loci method effectively, one needs a special training and a good deal of practice.

Constraints of Using Space in Thinking Without External Aid

From the cognitive investigation, the same phenomenon can be explained from two aspects: the availability of spatial structures and the capacity of the working memory.

Research shows that when spatial organization of items in the environment is congruent with elements to be remembered and their relations, both humans and other animals will take advantage of this structural similarity and exploit the congruence between spatial and logical structures. It will be less frequently used by reasoners if the relevant spatial organization is not available in the environment and need to be constructed either mentally as mental array or mental model or externally in form of spatial representation.

The other aspect may inhibit the use of spatial cognition in thinking process is the limited-capacity of the working memory. The relational processing involved in the construction of the spatial structure and the adapting between spatial and conceptual structures will be a demanding task for the reasoner. It will involve a heavy computational working load which is challenge to the processing capacity.

In the first century A.D, Quintilian had already noted the problem of the working memory overloading in the mapping process. "But will not the flow of our speech inevitably be impeded by the double task imposed on our memory? For how can our words be expected to flow in connected speech, if we have to look back at separate forms for each individual word?"

With all its great effectiveness and practical limitations, the loci method changed to be only an ancient story, which even not known by many. But the value of spatial cognition in thinking process revealed in this method and many other places has not and will never disappear. With the development of external aid, many of human's cognitive abilities and potentials are neglected. Although it is important to create devices to take over part of our laborious work, it will be more organic and promising to use new technologies bridging out our own strengths whose application is being inhibited. Research in this direction can amplify human cognition more actively, and can reach a new level of complexity. As stated Pinker, the spatial cognition of average three-year young child will be too complicate to be simulated by computational system. The way to build machine spatial cognition will inherently be effortful and decrement. However, applications which help human exploit spatial cognition to a new level will destined to be on an upward direction for a new human cognition.

External Aid for Using Spatial Cognition in Thinking

I consider the place where human cognitive ability is constrained from potential performance as the place where computation could play its role. Considering of the two main constraints, the availability of the spatial structure and capacity of working memory, one possible way to overcome the constraints is to construct the space as a real-time interactive environment on the computer, and to use the increased resource from computer memory for the space construction, information mapping, storage and retrieval. With the constraint burden being taken away, the strength of spatial cognition in thinking could be exploited more intensively. Reasoning in the corresponding space constructed on computer, most of the working memory could be used in the holistic information comprehension, in the recognizing of three-dimensional patterns, and in the spatial inference and manipulation of those representative entities for the abstract premise. This is an external aid in the execution of human spatial cognitive process, and not a separate aid prepared to be passively used.

Augment Human Cognition

This proposal of using external aid for incorporating spatial cognition in thinking process might sound strange when heard for the first time. But think of those many evolutions in human cognition we have already experienced, we will accept that any proposal based on reasonable theories may become facts taken for granted in the future. We don't know how strange the feeling was for ancient people to think of using book as external memory, but we do experience the growth of internet from a scientific topic to an indispensable part of our intellectual life. Much of the attractive future illustrated in Mitchell's "City of bits" has already realized only through a short period of time; the electronic name he mentioned indeed being used more frequently in our campus life than our real name. All these ongoing developments from technology are forming and reforming our modern mind.

In "Origins of the Modern Mind", Donald (1991) proposed three hypothetical transitions in the evolution of the human brain and mind. The first is the movement from the level of culture of apes to that of Homo erectus; the key innovation was the emergence of the most basic level of human representation, the ability to mime, or re-enact, events. The second is the move from the culture of erectus to that of Homo sapiens. The biological evolution of modern humans was completed during this long transition. Key event for this transition was the emergence of the human speech system, including a completely new cognitive capacity for constructing and decoding narrative. The third is quit recent and largely nonbiological marked by the emergence of visual symbolism and external memory as major factors in cognitive architecture.

In his proposal, Donald views the amplification of cognition through new technologies a status as high as those of the first two revolutions. He considered this a great transition which happened without major genetic change and reconfigured our mental architecture in nontrivial ways. I think all our energies of using computation to amplify human cognition are pushing forward this third evolution. Donald's theory reminds us of the profound meaning of explorations in this direction, helps to raise serious attention to proposals which may seem to be imaginal at the first sight.

Computational Imagery

Research on computational imagery by Glasgow has already arrived an exciting stage of developing computational applications based on the study of human cognition, specifically the nature and property of mental imagery. But there is still a big difference between her research and what I propose. Glasgow's goal is to construct a knowledge representation model based on the mechanism and process of human mental imagery, and use this model for problems whose solutions by humans involve the use of mental imagery. The role of computation in her research is to explicitly perform what mental imagery does, and to provide people a better environment for representing, retrieving, and reasoning spatial and visual information. The psychological theories and cognitive models of mental imagery are only used as a frame work for constructing a new tools. The application simulates the strength of mental imagery process, and adds new features to overcome its limitation. The primary concern in that research is not a strict cognitive model for imagery, but the efficiency, expressive power, and inferential adequacy of the application.

"Computational imagery involves tools and techniques for visual-spatial reasoning, where images are generated and recalled from long-term memory and then manipulated, transformed, scanned, associated with similar forms (constructing spatial analogies), pattern matched, increased or reduced in size, distorted, and so on. In particular we are concerned with the reconstruction of image representations to facilitate the retrieval of visual and spatial information that was not explicitly stored in the long-term memory. The images generated to retrieve this information may correspond to representations of real physical scenes or abstract concepts that are manipulated in ways similar to visual forms." The reason they choose to use mental imagery as the base model to develop the new tools for spatial reasoning is from their theory study that "Although there are varying strategies for retrieving spatial information and solving problems concerning spatial relations, research has suggested that humans typically use mental imagery for spatial reasoning. (Farah, 1988)" The fundamental question addressed in their research is "What are the underlying processes involved in mental imagery, and how can corresponding computational processes be efficiently implemented and used to solve real-world problems?" (Glasgow & Papadias, 1998)

How

Construct the Space on Computer

Availability of Spatial Structure and Problem with Working Memory

As mentioned in last section, whether spatial schemas are used as memory or thinking structures is related to whether the relevant spatial organization is available in the environment or can be constructed effortlessly. But situations where the spatial structure is most readily available either physically or as mental imagery are not necessary situations where the aid from spatial cognition is most needed. The spatial relation of concrete or spatial stimulus materials can be easily set up, but the inference with aid from spatial perception may be more needed in abstract and highly unstructured tasks. This paradoxical fact presented more necessity for the construction of the space with external aid.

Results from related research further reveal that even though the inference involved with the aid from visuospatial perception can alleviate much of the processing load of thinking relying on the processing of prepositional information, the load to build up and maintain the spatial model raised new challenge for the working memory. This also shows the importance of moving the new working load external.

Denis (1988) analyzed from experiments by Kohler (1969) and Barolo et al. (1988) that "Within certain limits of mental load, holistic transformations seem to be helpful for efficient processing to occur; beyond these limits, the cognitive system is overloaded and unable to process information appropriately." In situations when much effort is needed to picture the data of the problem, and to integrate the relations, the working memory may reach the limits of its processing capacities, and many of the advantages of spatial-analog thinking will be counterbalanced by the additional load placed on subjects' working memory.

In his research program on analogical thinking, Morra reports that "While adults exhibit a strong tendency to code spatial descriptions in the form of analog representations, children below the age of nine tend to use a strategy based on verbatim storage of sentences." This finding suggests that "the amount of available mental capacity determines the size of representation a person is able to handle (which explains young children's greater reliance on verbatim storage). The construction of a highly integrated cognitive structure, such as an image reflecting complex spatial relationships, taps resources which are still limited in young children." (Denis, 1988)

Image Retain Problem of Mental Imagery

Another reason for maintain the spatial structure externally comes from the neuropsychological analysis of image retain in the mental imagery process.

In the process of using imagery in reasoning one first generate a pattern in the visual buffer either by combining familiar objects or parts employing novel spatial relationships, or by shifting the attention window systematically and marking its path with a swath of activation "mentally draw" in the visual buffer. There may need a conversion of abstract material to particular patterns in the image. The pattern is then inspected for the problem solving. There may also involves alteration of patterns in images, and new properties becoming evident are encoded along with the transformation. To operate on the patterns and "see" the result, the image needs to be retained for substantial amounts of time.

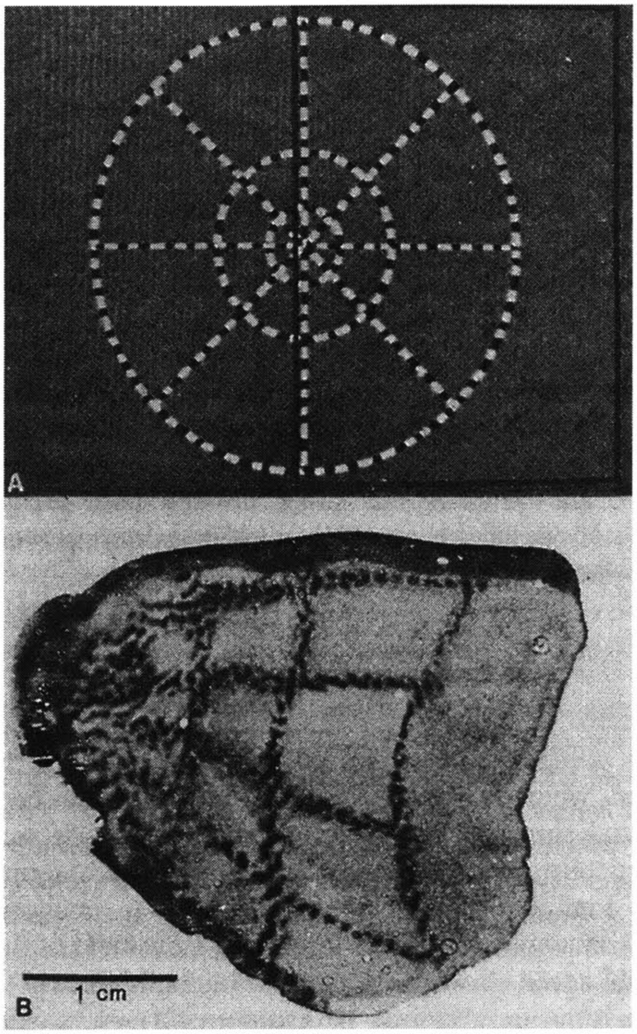
Based on the inference that mental images occur in the same visual buffer that is used in perception, properties that affect perception should also affect imagery. In perception images do not linger very long. Since our perception of the visual world comes from rapidly scanning from point to point, if images do not fade rapidly, they would smear and become overlaid. Thus, imagery images get from patterns in the visual buffer are also transient, which can only be maintained in a degrade form and only for a brief period of time.

For this reason, retaining a mental image requires effort, the amount of material that can be held in an image and the amount of time an image can be hold are both limited. This presents a problem of using imagery in thinking, since most reasoning tasks using imagery cannot be carried out instantly, and imagery are more useful in difficult problems which need more time to complete.

Image retention is accomplished by reactivating representations in the pattern activation subsystem. Each part or object in the same image is activated and reactivated individually. Each of such operation requires time. And as soon as a unit is activated in the visual buffer, it begins to fade. As each part is being refreshed, others are fading. The speed of the fading process, the speed of the refresh process, and the speed of shifting from one part to another define the number of parts or objects one can maintain in an image.

Experiments for the Inference of Identical Visual Buffer for Both Perception and Imagery

Input from the eyes arrives at the visual buffer structure which is spatially organized in much the same way as an array in a computer can be spatially organized. In the brain, the visual buffer corresponds to areas that preserve the spatial structure of the images that strike the backs of our eyes. Tootell et al. provided dramatic evidence for the existence of such spatially organized areas. They trained a monkey to stare at a pattern that looked something like a bulls eye with spokes coming out of the middle. There were little light bulbs spaced along the circles and spokes, which blinked on and off. The animal was then injected with 2-deoxyglucose, a radioactive kind of sugar. The more a given neuron worked as the animal viewed the pattern, the more of this sugar it used and the more radioactivity lodged in it. The animal was sacrificed and its brain, in essence, "developed" (much like one can develop certain kinds of photographs). The radioactive tracer allowed Tootell and his colleagues to observe which cells were most active when the animal was seeing the pattern. The pattern they saw on the brain is illustrated in the figure.



Pattern the monkey stared at and neurons (from one hemisphere) activated.
From Tootell, Silverman, Switkes & De Valois [AAAS., 1982]

As expected, an image of the pattern was spread out over the back of the animal's brain. The pattern that falls on the retina is itself sent to the brain, and this pattern is physically laid out on the surface of area V1, the first visual area on the visual pathway. This area is organized in the same way as the retina, and hence preserves the spatial properties of images that fall on the retina.

Fox et al. experimented on humans by injecting a small amount of radioactive material mixed into the blood. The more that different parts of the brain need oxygen and nutrients, the more blood is shunted to them. Thus by recording the amount of radioactivity in different parts of live, thinking human brains, areas which are most active during a given task can be detected. Their findings from the experiments demonstrated that human V1 is also spatially organized, with a systematic relation between the parts of the retina that are stimulated and the corresponding parts of cortex that are activated. (Kosslyn & Koenig, 1992)

Stable Environment for Further study, Interaction, and Communication

A three-dimensional interactive environment provides people a place to externalizing their thought processes. One can actively manipulate the spatial structures much as move and modify them internally in mental space. Structures or entities in the scene on the computer are easy to form and reform and allow novel combinations or transformations impossible in reality. It is between the space in mental imagery and the space in reality; it is more stable and easy to grasp than imagery, and also more flexible than in reality.

This process is to externalize the mental screen in imagery with computer screen. Many of the anecdotal accounts of creative imagery involve external aid in the imagery discovery process; for example, Picasso produced 45 preparatory compositions during his painting of Guernica (Gardner, 1993), and Watson and Crick utilized both image manipulation and physical manipulation of cardboard models of molecules during their investigation into the structure of NDA (Shepard & Cooper, 1982).

In the reasoning process, a major problem is to keep track of the models of premises. Compared with verbal and logical medium, perceiving the visual manipulation shows a more direct route than conceiving verbal description of the inference. The verbal description needs to be parsed and a compositional semantics needs to be used to construct its prepositional representation, which is then used in turn to construct a new status of the premises model. The spatial structure also makes alternative possibilities explicit. Compared with the spatial structure in mental imagery, a stable and external visual environment can overcome the limitation caused by image retain in imagery, reasoner can contemplate the problem with a holistic view of the whole movement of the manipulation and evolution. The external space allows an interactive thought process to operate repetitively on its own products.

An external environment can also facilitate group thinking and communication, it can become a thinking process shared with colleagues and can be mutually formulated.

LOD for More Places and Relationship with Depth

LOD (Level Of Detail) is a common concept and technique in virtual environment programming, which allows to specify various levels of detail or complexity for a given object. The version displayed is based on the distance between the object and the user's eye point.

It is possible to define an element of a space change to be a new sequence space of when the user get close enough to that element. Thus there can be subspaces open up when the user reach some elements in the main space. LOD will then be a good way to introduce infinite spaces and still keep track of the structure of the spatial relationship in a holistic view. By this we can "equip ourselves with a large number of places" which the environment in reality cannot provide. For situations when the environment is used for memory purpose, places or loci created by this mechanism are more efficient for organizing information, since they can be traced based on the cue from different levels. The mapping of information to places in architectural space in the loci method is by assigning the content to a location arbitrarily. There is only a sequential relationship among the locations which helps the recall. Bu this relation is one dimension, by a mapping like this all the content is placed on a same level. When locations are organized through the mechanism of LOD, the relationship adds a new dimension with depth. Information can then be organized by category. One may argue that it is quite possible to imagine space inside space. But as mentioned before, there is problem for image retain even in the maintaining of spatial relationship on one level, it will be more prone to be lost in an organization with depth.

New Tools and VR Environment

Interactive 3D programming, interactive 3D software and scripting provide a convenient programming environment for developing the front end of the application.

The fast hardware increment makes it possible to accomplish real time 3D rendering on normal computers.

Immersive or Semi-immersive Virtual Reality environment will provide a better environment than the 3D world on computer screen, and will be more impressive for some special situations which rely more on the real-time real-place perception.

Explore New Perception, Conception and Relationship with Space

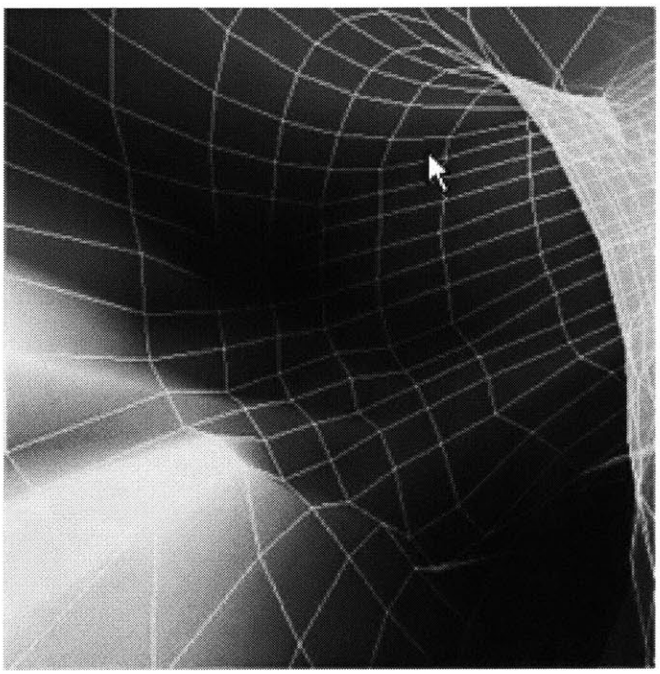
The use of "real" or "fictitious" had been a debatable topic forever in the memory treaties constituting the art of memory. "'Real' places are real buildings of any kind used for forming places in the normal way in the mnemotechnic. 'Fictitious' places are imaginary buildings or imaginary places of any kind which the author of Ad Herennium said might be invented if not enough real places were available." (Yates, 1966)

There actually exist more reasons for exploring new spatial possibilities other than achieving a large amount of places. The structures of many abstract information or concept are usually too complex to be mapped onto architectural spaces which following strictly rules in physical world. The programming for digital space provides the possibility to explore new perception of space by challenging the visual limit, explore new relationships with space by going beyond the physical constraints, and explore new conception of space by combining philosophical thinking. Resulting forms or experiences of these explorations may match very well the topics being thought about, may represent their structures and properties more pertinently. Even though our study of spatial cognition start from the spatial vision and perception of the three-dimensional physical world around us, we may reach a new hybrid cognition of space in such digital environments, much as the extending of our visual cognition by computer graphics, cinematic special effects and other electronic visualgraphic forms.

Rethinking Space Related Questions

There are many potential questions can be experimented through computational process. What would the space look like when changing the point and angle of view to the extent beyond the limit? What would the feeling or subjective experience be when conventions about space is redefined? For example when a person walks toward and reaches a wall of a room, the wall changes to be the floor and the floor changes to be the wall behind. Could we change the reference system of navigation, so it is not we moving through the space but the space moving through us? How to re-interpret the relationship between time and space when virtually both time and space can be non-linear? Can we experience space through cuts, like the way we experience time? How to conceive a discontinuous space? Can a composite vision from different temporal and spatial positions bring up a sense of simultaneous occupation? What is the concept of inside and outside, is there a division? What can be revealed by the study of Klein bottle? What can those new ways of communicating and interacting with spaces bring up to us, such as more spaces will be opened up at the point of attention? What would be the spatial experience of disorder, displacement and distraction?

These questions can be thought about with 3D programming as the tool much as the way we use pencil to outline our ideas. In the course Superficial Spaces (GSD7303), space was being studied down to meshes, surfaces, and curves, from its formation, evolution, and differentiation. I was so obsessed by the graceful manipulation of space, and began to have an idea for experiencing the sculpture of space. In the final project, I programmed from scratch, realized aspects of the feeling for the pushing and pulling little by little. And it is finally finished as an environment where space can be re-formed to desired shape. The tension that space poses to a person inside can also be sensed from the transparency of the area being sculptured. When pushed out, the surface become more transparent; when pulled in, it changes to be more opaque. This is a sculpture from inside, and a sculpture of nonsolid material. It is in forms of the sculpture of surfaces, but also sculptured the matter enclosed by the surface, the void, the space. This helps us realize a new relationship with space which is impossible to be experienced in reality. The process of this exploration suggests the possibility of using programming to think about other space related questions listed above.



Screenshot of the Sculpture Space application.

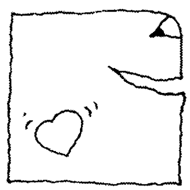
Get Out of the "Spaceland"

Can we perceive the high dimensional space by experiencing it but not only conceiving it from the definition? Can such an experience help us understand or discover more rules of the nature? It is said that without the tool of infinite-dimensional spaces, modern physics would be almost impossible. For example, when you measure a quantum system, you are said to "rotate the state vector," an abstract line of precisely defined length and orientation that represents the systems that constitute a Hilbert space. Not complacent as a century ago, scientists nowadays are particularly aware of the limits of human sensory perception. And it will be extremely difficult to imagine worlds outside of our experience. But based on previous thinking and metaphors of higher dimension, it seems to be quite possible to use computation to help people accomplish such an experience.

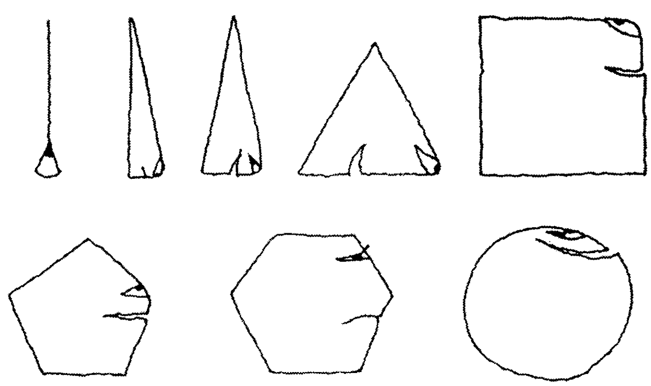
Metaphor from the Square in Flatland

In "Flatland", Edwin Abbott, told the story of a square who takes a trip into higher dimensions. Abbott's great imagination and spiritual thinking revealed to us the vivid life of a two-dimensional world: the nature, climate, and house in Flatland; the inhabitants of Flatland; how do they see, think and live. The difficulties of Square, the hero of the book, in understanding the third dimension are the same as our problems with the forth dimension and his trip to Spaceland gives us many hints for possible process to experience the forth dimension.

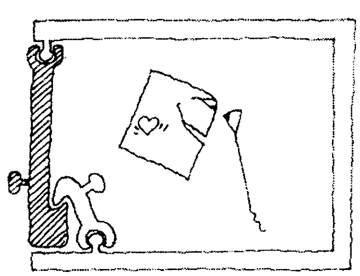
Rucker gives characters in the story many interesting figures in chapters in his books which related to "Flatland".



Square

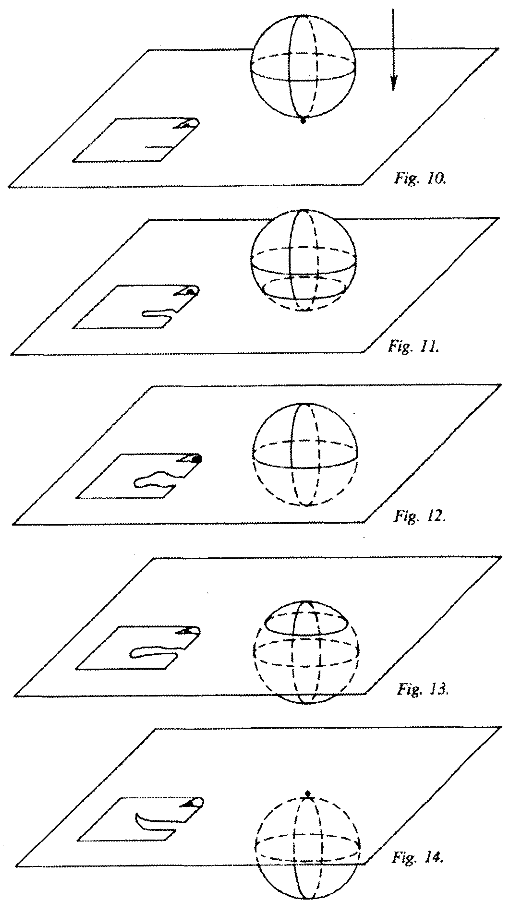


Eight Flatlanders: Woman, Soldier, Workman, Merchant, Professional Man, Gentleman, Nobleman, High Priest



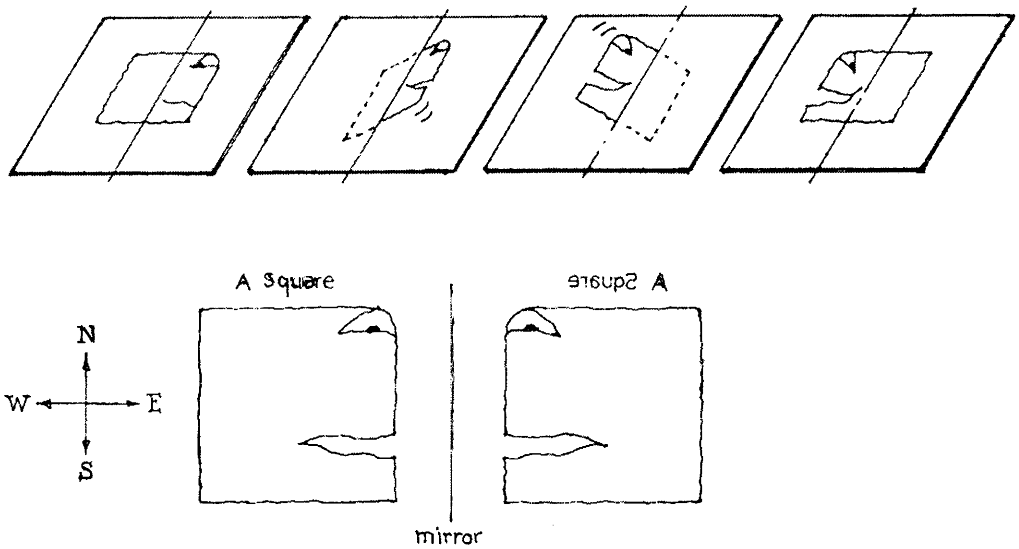
Square and his wife at home.
From Rudy Rucker, *The Fourth Dimension: Toward a Geometry of Higher Reality* [Boston: Houghton Mifflin Company, 1984], 10, 13, 16.

One evening, when Square and his wife are comfortably sealed up in the safety of their home, a voice suddenly speaks to him out of nowhere. A point, then a circle appears in the confines of their tightly locked house. That is Sphere, who comes to inform him about the third dimension.



Sphere moved through the Flatland.
From Rodolf v.B. Rucker, *Geometry, Reality and the Fourth Dimension* [New York: Dover Publications, Inc., 1977], 5.

The only way by which Sphere could finally convince Square of the reality of the third dimension was to actually lift him out of Flatland and show him what it was like to move in three dimensions. (Rucker, 1977)



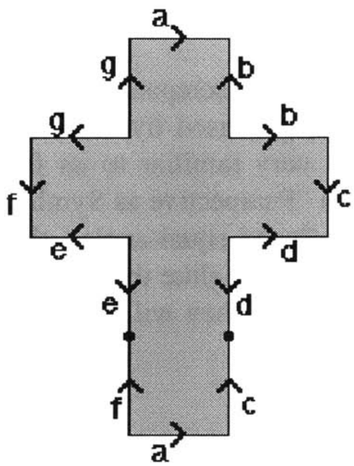
Square turns over and becomes his mirror image.
From Rudy Rucker, *The Fourth Dimension: Toward a Geometry of Higher Reality* [Boston: Houghton Mifflin Company, 1984], 42, 43.

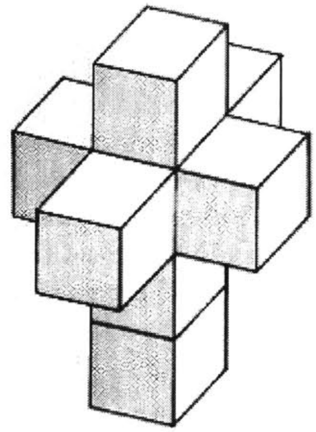
Square yells to Sphere, "Turn me over. Turn me over and then my very body will be proof that the third dimension exists." And he was finally turned into his own mirror image, turned to be "object of horror to the god" in flatland, since everyone in the Flatland was built so that if the eye was towards the north, the mouth was towards the east, and no one would look like the mirrored Square without experiencing a three-dimensional rotation.

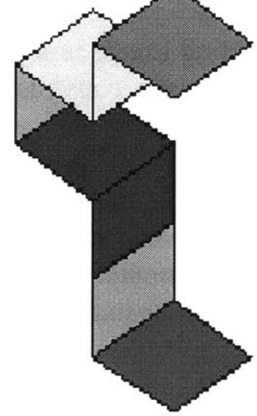
Is there a chance that this could happen to us? What would be the creature of the fourth dimension comes to lift us out of the Spaceland like the Sphere? What would be the dimension for us to accomplish a rotation like the Square? Similar to the invasion of Sphere into Square's locked room, our enclosures have no walls against the fourth dimension; everything is open to a spectator from there.

Fold the Unfolded Hypercube

A box can be split open, unfolded and laid flat in a plane with labels and arrows as shown on the edges tell us how to reglue it back together again. A four-dimensional cube (hypercuber) can also be unraveled into its lower components of three-dimensional cubes in the same way as for the box. There is a set of abstract instructions for folding back a hypercube by folding up strips along sides of the unfolded hypercube so that pairs of squares with the same color get folded into a single square.







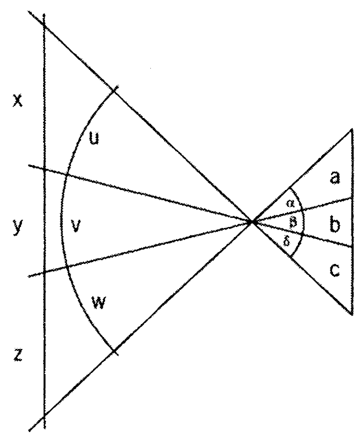
Unfolded Box **Unfolded Hypercube** **Gluing Instructions**
[Images at http://www.math.ohio-state.edu/~fiedorow/math655/hypercube.html]

Life in such an unfolding and folding space has been depicted in a science fiction by Robert Heinlein. An architect built his house in the shape of an unfolded hypercube. During an earthquake, the house gets folded into a hypercube. Initially there is nothing unusual noticed by the architect, since each individual room looks exactly the same as before. However, something amiss is felt as soon as he tries to leave the house. He will never encounter any sealed barriers, and is actually trapped inside a folded house. When trying to get out from the front door on the ground floor, he reemerges upside down through one of the (formerly outward facing) windows of a room formerly overhanging from the third floor. When he then trying to leave that room via the skylight, he find himself get into the topmost room via a window. And the temptation for leaving through the skylight of the topmost room turn out to be back to the ground floor again via a trapdoor.

Could people get the feeling of walking in the four-dimensional space when we set up such an environment by folding the unfolded hypercube on the computer, and let people wander as they want? Could such a spatial tour be helpful for understanding the structure of some high dimensional concepts by perception? Scientists have even bold ideas of thinking about the universe as a house like this with rooms billions and billions of light years across. Lying on the ground floor of the house with the trapdoor open, looking straight up through the stairwell in the central axis through the skylight of the top floor, if the speed of light were infinite you would be able to see the back of your head while looking forward. Or, after a long space flight around the universe, you will find your right and left sides got inverted upon your return, much as the mirror image of Square.

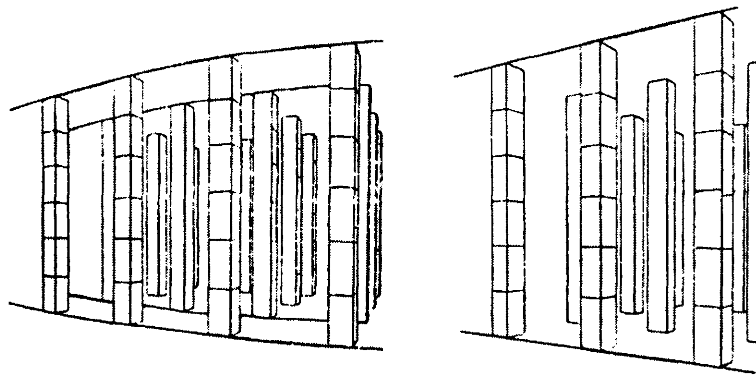
Space Seen from Curvilinear Perspective

Retina image is a projection on a concave surface. There is thus a discrepancy between the image constructed by linear perspective and what is actually sensed by our retina. This can be noticed from the marginal distortion which are very familiar to us from photography. A simple example has been stated by Panofsky in "Perspective as Symbolic Form": a line is divided so that its three sections a, b and c subtend equal angles, these objectively unequal sections will be represented on a concave surface (like the retina) as approximately equal lengths; whereas if projected on a flat surface they will appear, as before, as unequal lengths.



Explanation of the "marginal distortions."
From Erwin Panofsky, *Perspective as Symbolic Form* [New York: Zone Books, 1991], 32.

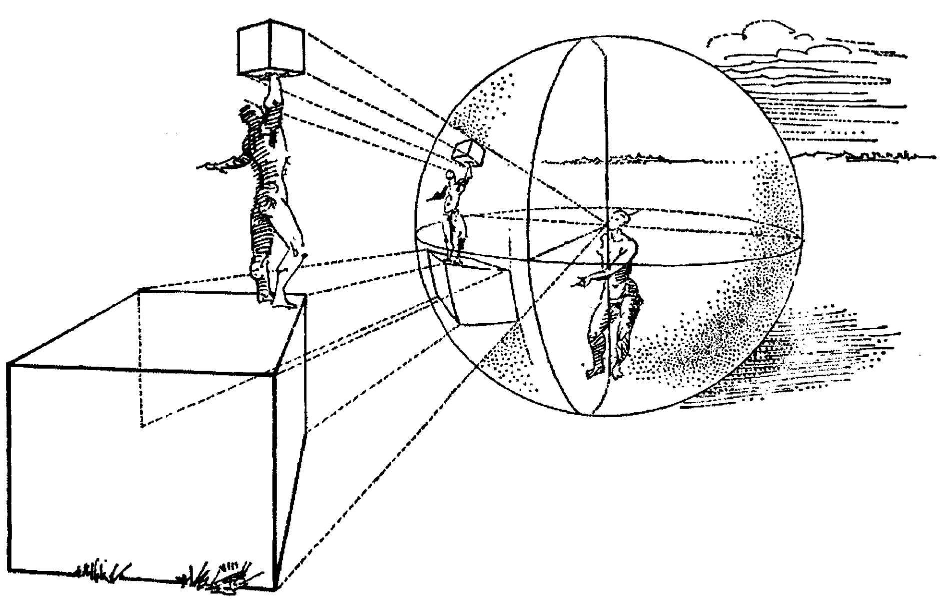
Alongside this purely quantitative discrepancy, there is a formal discrepancy as well. "While perspective projects straight lines as straight lines, our eye perceives them (from the center of projection) as convex curves. A normal checkerboard pattern appears at close range to swell out in the form of a shield; an objectively curved checkerboard, by the same token, will straighten itself out. The orthogonals of a building, which in normal perspectival construction appear straight, would, if they were to correspond to the dactual retinal image, have to be drawn as curves. Strictly speaking, even the verticals would have to submit to some bending." (Panofsky, 1991)



Hall of pillars constructed according to "subjective" or curved perspective (left) and according to schematic or linear perspective (right).
From Erwin Panofsky, *Perspective as Symbolic Form* [New York: Zone Books, 1991], 33.

The observation and consideration of the curvature nature of the optical image can be found at many places in antique optics and art theory. For example, "columns must be subjected to entasis in order not to appear bent, epistyle and stylobate must be built curved in order to avoid the impression of sagging." The curvatures of the Doric temple which we got familiar with from the very beginning of our architectural training are actually practical consequences of such findings.

In his book "A treaties on the curvilinear perspective of nature and its applicability to art", Herdman (1853) claimed some principles for circular perspective. Flocon & Barre (1968) created the first systematic analysis and practical solution for this new way to depict the world. The very fundamental concept which makes it different from the linear perspective can be seen from the following figure.



From Albert Flocon and Andre Barre, *Curvilinear Perspective* [University of California Press, 1987] 104

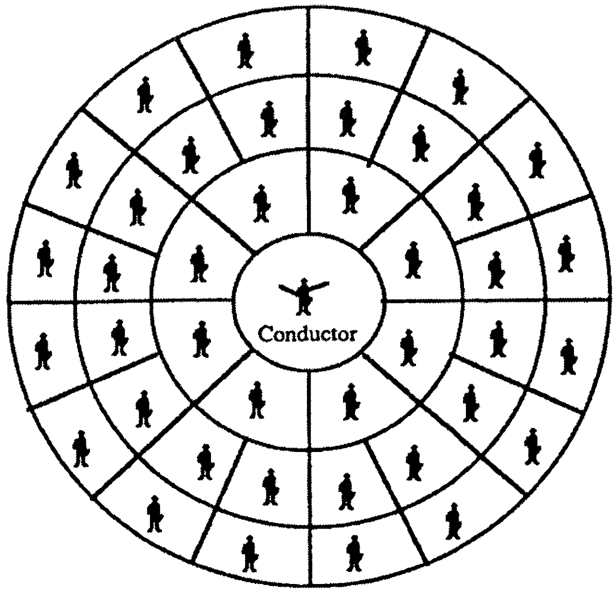
I am not attempting to advocate replacing the linear perspective with this little-understood system. But it will be worth a try to implement this in the creation of a computational environment. A digital environment formed by images constructed from curvilinear perspective may help people rediscover the curvatures of our optical world. The change to such a new representation of the space systematically may bring up unexpected perceptions of space in the digital environment. Spatial relationships may be more accurately perceived in such an environment which is closer and more faithful to what we see. By enriching the peripheral vision, such a new computational representation may enhance our holistic comprehension of spatial relationships in digital environment. There are applications simulating fisheye views for focus + context display of information. Considering of the fact we human see the world, there is already the characteristic of focus + context. With curvilinear perspective system bridging this "reality" to the computational simulation, we may never need to introduce the extra model of fisheye view. This is only an obvious character of such a space constructed from curvilinear perspective. There may be more potential strengths hidden there waiting to be discovered during our navigation inside such a space.

Incorporate and Interpret Computational Theories in New Ways

Besides using computer's processing ability to relieve the working memory problem involved in using spatial cognition in thinking, and using 3D programming to set up on computer the spatial environment either real or not exist in reality, new computational theories and new ways to interpret them could also be a helpful factor in incorporating the strength of spatial cognition into abstract thinking.

When talking about parallel computation, what comes into people's mind will be large scale computing, and attention for calculation speed. Virtual topology is a way people employed to facilitate the calculation speed by effective algorithms developed based on the virtual spatial relationship among the processors (or say processes since it is virtual). But actually, we could use this computational architecture from a new way and for a purpose other than high speed. We could specifically focus on the design and organizing of the virtual topology among the processes and also take advantage of their "point-to-point massage-passing" way of communication to flexibly set up varieties of relationships both spatially and socially among them. These could be used to simulate or reveal the structure of complex and dynamic concept and logics. When using the SIMD (Single-Instruction Stream Multiple-Data Stream) architecture, each process could be thought of as a basic unit with same sets of behaviors with the virtual topology as the structure to organize them, and each one of them would be affected both by people's interaction with it and by information from other unit(s) related to it. The design of such process can also be strengthened by theories about cellular automata machines and autonomous agents.

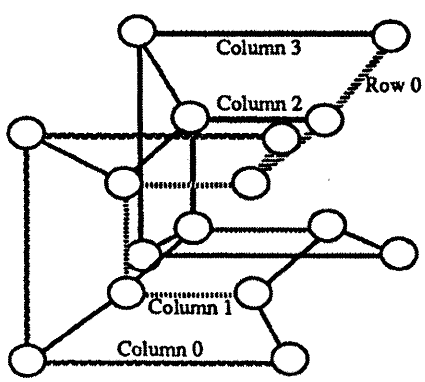
Richardson, a British meteorologist, first expressed the attempt to forecast weather using numerical computations. The basic shape of the parallel computing architecture for modern weather forecasting can already be seen from his dream: "Imagine a large hall like a theater.... The walls of this chamber are painted to form a map of the globe.... A myriad of computers are at work upon the weather on the part of the map where each sits, but each computer attends to only one equation or part of an equation. The work of each region is coordinated by an official of higher rank. Numerous little 'night signs' display the instantaneous values so that neighboring computers can read them.... One of [the conductor's] duties is to maintain a uniform speed of progress in all parts of the globe.... But instead of waving a baton, he turns a beam of rosy light upon any region that is running ahead of the rest, and a beam of blue light upon those that are behindhand." (Parhami, 1999)



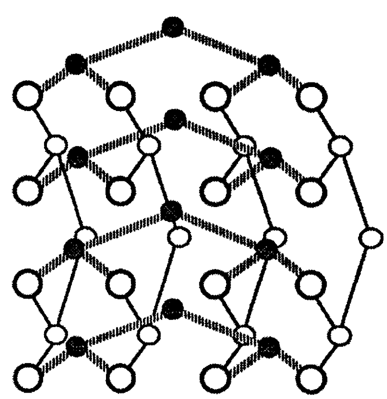
Richardson's circular theatre for weather forecasting calculation.
From Behrooz Parhami, *Introduction to Parallel Processing: Algorithms and Architecture* [New York: Plenum Press, 1999], 14.

Richardson's dream had already captured the concept for virtual topology, which is the main factor for enhancing calculation speed in modern weather forecasting computation.

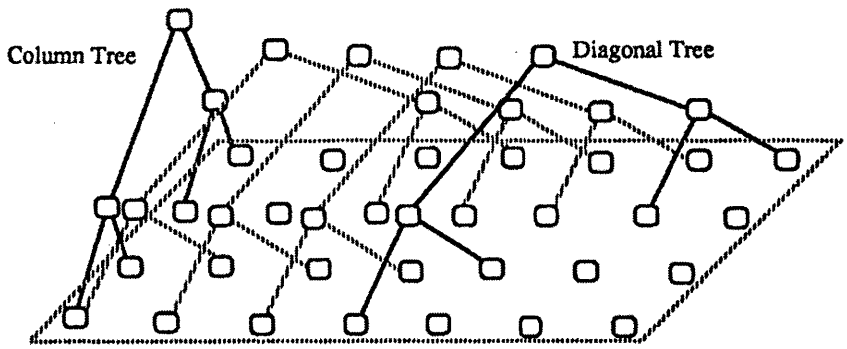
The design of MPI (Message-Passing Interface), the portable standard for programming parallel computers, is based on using message-passing to exchange data between, and synchronize the parallel tasks. Thus communication is the core for this standard and organizing relationships between processes becomes an important content. There are point-to-point communication, collective communication, intra and inter communicators. And often the processes are arranged logically in a topological pattern, which is referred to as "virtual topology". There are Cartesian topology, graph topology, mesh-based topology, and network topology. There are 1D linear or ring topology, 2D rectangle, cylinder, or torus topology, and topologies in three or more dimensions.



4x4 mesh as a subgraph of 4-cube



Mesh of tree architecture with three levels

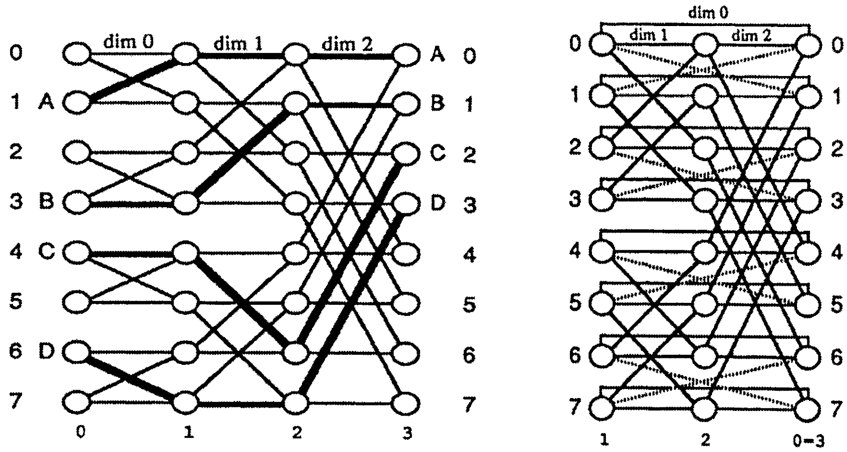


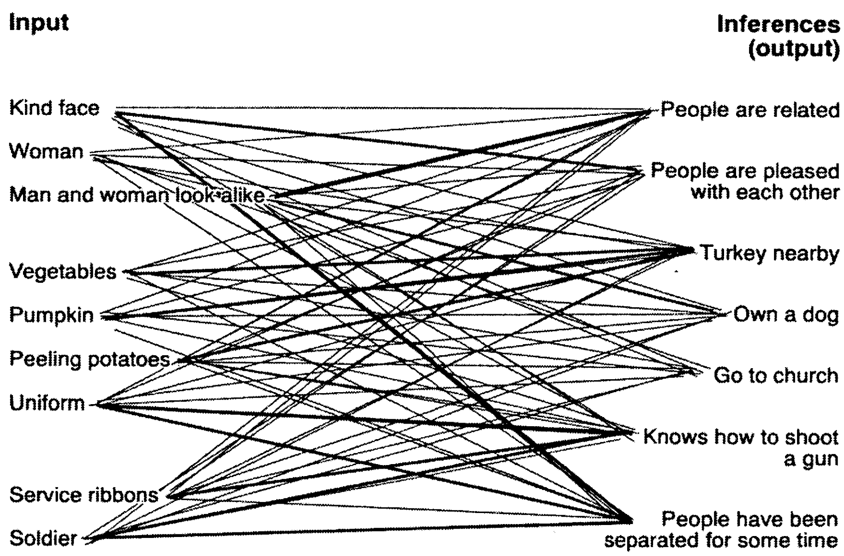
Mesh of trees variant with row, column, and diagonal trees.
From Behrooz Parhami, *Introduction to Parallel Processing: Algorithms and Architecture* [New York: Plenum Press, 1999], 267, 249, 251.

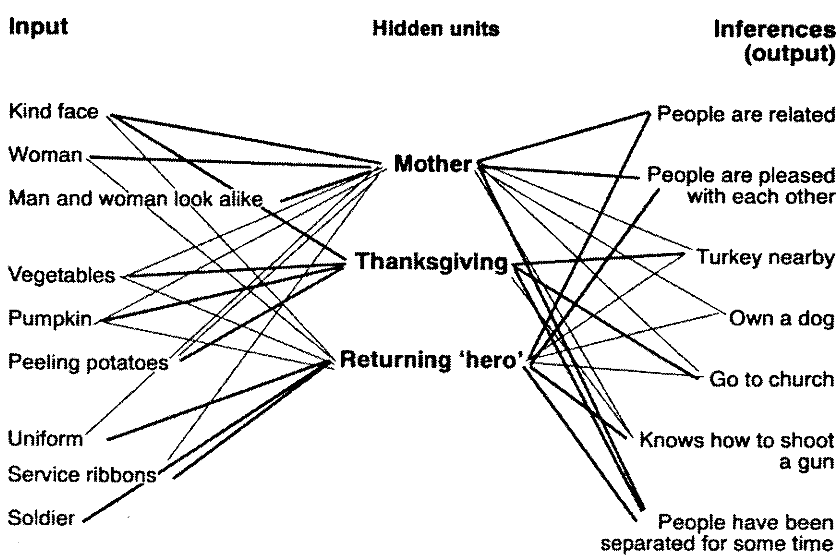
The typical use of virtual topology is to be as the logical base for powerful algorithms to achieve high performance computing, which is the typical aim for parallel computation. Here the communicational and spatial concepts are used indirectly to achieve fast computation. However, we could think from a somewhat reverse way, in the kind of applications where communication and spatial relationship is the main topic, this system could be even more helpful. Both the concept and the programming for the communication and virtual topology can help to construct a structure for the interaction among units and the evolvement of the system as a whole. The program executed on each processor can be seen as character and behavior of each unit. The concepts for connectionism and bottom-up evolving mechanism are discussed and implemented more explicitly in theories for cellular automata and autonomous agents. They both propose the decomposition of the intelligence of complex, extended systems into individual behavior generating modules, whose coexistence and co-operation let more complex behaviors and dynamic consequences emerge. The new use of these computational theories could be outlined as:

Virtual topology + communication + self behavior → dynamic evolving spatial schemas for reasoning and comprehension

In my research study, I find an interesting similarity between the analyzing of the routing on hypercube topology and the analyzing of the neural network model for conceptualizing information.


dim 0
dim 1
dim 2
0
1 A
2
3 B
4 C
5
6 D
7
A 0
B 1
C 2
D 3
4
5
6
7
0
1
2
3
dim 0
dim 1
dim 2
0
1
2
3
4
5
6
7
0-3


Input
Inferences (output)
Kind face
Woman
Man and woman look alike
Vegetables
Pumpkin
Peeling potatoes
Uniform
Service ribbons
Soldier
People are related
People are pleased with each other
Turkey nearby
Own a dog
Go to church
Knows how to shoot a gun
People have been separated for some time


Input
Hidden units
Inferences (output)
Kind face
Woman
Man and woman look alike
Vegetables
Pumpkin
Peeling potatoes
Uniform
Service ribbons
Soldier
Mother
Thanksgiving
Returning 'hero'
People are related
People are pleased with each other
Turkey nearby
Own a dog
Go to church
Knows how to shoot a gun
People have been separated for some time

Packing routing on the hypercube (top left). Wapped butterfly networks (top right).
From Behrooz Parhami, *Introduction to Parallel Processing: Algorithms and Architecture* [New York: Plenum Press, 1999], 290, 305.
Associations between input features and inferences, based on Rockwell's *Thanksgiving* (middle).
Hidden units, input, and inferences in Rockwell's *Thanksgiving*. Strength shown by width of the connecting line (bottom).
From Robert L. Solso, *Cognition and the Visual Arts* [MIT Press, 1994], 259, 260.

They both involve the analyzing of the connections between units (or nodes), hidden units (or inter-node). They both study the thickness of these connections, even though one think of them as relations, the other think of them as paths.

In "Cognition and the visual arts", Solso analyzes the comprehension process down to the neurobiological level. He outlined the neurological routine for artistic perception and cognition as through three stages. "Visual information from the physical world is detected by the eye (stage 1) and is transduced to neural energy and passed along to the visual cortex (stage 2), where it is initially processed in terms of primitive shapes and forms. Visual signals are analyzed in terms of simple contours, such as vertical and horizontal lines, curved lines, and angles. These elementary forms are combined into larger units, such as basic components of an entire scene. Information is further processed by other parts of the cerebral cortex (stage 3) that are activated in a massively parallel fashion in which neural impulses are sent to widely distributed regions of the brain and processed simultaneously. Semantic processing also happens during this stage. The composite effect of these processes leads to an interpretation of the visual signals in light of previously stored information." Adopting the metaphor of the third stage of information processing in which inferences are drawn upon a huge number of neurons activated by massive parallel processing, there comes the neural network models for understanding the process of generalization and inference. The fundamental concept is that "information can be conceptualized as having units and connections between units. The connections between units can be modified: they can grow stronger or weaker so that the output is appropriate to the input." Between input and output there are mediating "hidden units" which are fundamental to the model in that they enable the network to form representations of the outer world. (Solso, 1994)

Both based on parallel processing, similar in spatial form and organizational model, virtual topology and neural network model present the possibility for a congruence of them on a deep level and verify the feasibility of the attempt to use parallel programming in a new way for aiding reasoning spatially.

Chapter 6 Conclusion and Recommendation

In the preface of "Conceptual Spaces", Gärdenfors (2000) humorously described his research as a centaur standing on four legs which are philosophy, computer science, psychology, and linguistics (and there is a tail of neuroscience). Since these disciplines pull in different directions, he is worrying that this will make it satisfy no one. "Philosophers will complain that my arguments are weak; psychologists will point to a wealth of evidence about concept formation that I have not accounted for; linguistics will indict me for glossing over the intricacies of language in my analysis of semantics; and computer scientists will ridicule me for not developing algorithms for the various processes that I describe." He further explained his aim as "unify ideas from different disciplines into a general theory of representation" and "present a coherent research program that others will find attractive and use as a basis for more detailed investigation."

Researching on an inter-disciplinary topic, I am in a quite similar situation, and also have the similar concern. This research started from my strong desire to explore potential use of space and spatial thinking. It then goes to the area close to cognitive science, and with support from computer science as means to realize the breakthrough. There is a risk that my ideas related to cognitive science and computer science might be too naïve. But I think a research standing outside either field could at least present to researchers concepts from a unique point of view, which may give them inspirations for further research.

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