The Glass Bead Game

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Chapter 1.

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Visual Knowledge

"This same eternal idea, which for us has been embodied in the Glass Bead Game, has underlain every movement of Mind... with the dream of pairing the living beauty of thought and art with the magical expressiveness of the exact sciences [1]."

Hermann Hesse, *The Glass Bead Game*

Our lives are filled with images. Everyday we see signals, read signs, and learn symbols. We find our way with maps, look for news and bargains in newspapers, calculate our bills and taxes. We turn printed music into wonderful sounds, often without conscious effort. Icons fill our churches, synagogues and mosques, dot our computer screens, and are sprawled on billboards, on clothing and advertisement pages. Architecture and art conspire to fill our views with meaningful shapes and form. Pictures capture an instant in time, while movies and video entertain us with visual motion. We live in a visual world, full of information transmitted by light.

Writing is the verbal made visual, put into physical form as combinations of letters incised in clay or stone, or on a printed page, or on a computer screen. We understand the words as we see them because the visual impressions on our retinas ultimately connect with the language centers of our human brain. Similar mental processes occur for mathematics and music. Mathematical symbols represent something specific, some thought or quantity, or a relationship between abstract concepts. Notes on a score represent pitch and duration. We see the symbols, visually, and we know what they represent. But how do we know?

More neurons are used to transmit visual sensory information to the brain than for any of the other senses. The retina, the light-sensitive layer at the back of the eye, has a special status above all other sensory organs as a direct extension and outgrowth of the brain itself. In the early fetus, portions of the nascent forebrain extend forward to develop eventually into the eyes and retinas. The mature retina is composed of multiple interconnected layers of neurons that take the images coming into the eye and begin to analyze them for spatial relationships. After the retina performs considerable neural computation, the visual information is coded into electrochemical impulses that are the language of the brain and of intelligence. This all happens before the signals are even transmitted to the visual cortex of the brain. Thus we already have intelligence in our eyes. Natural selection has driven the evolution of organisms who have sophisticated image acquisition and analysis capabilities because the visual image is an information format with significant advantages for survival. None of the other senses can give the type of explicit spatial information that eye and vision can, especially the ability to provide information about distant predators or prey. What is it about the image that makes it so informative?
A visual image such as a picture is a parallel data structure. That is, all points in the picture or scene either emit, transmit or reflect light all at the same time—in parallel. A single square centimeter of a picture has well over a million points of light all emitting together. When the image falls on the retina, hundreds of thousands of micron-size receptive fields in the retina process and send information simultaneously to the brain. The parallel data rate is over a megabyte per second — comparable to the data transfer rate of a computer hard drive [2]. By considerable contrast, during oral communication the ear receives words one at a time — that is, serially — at the rate of only a few bytes per second. The parallel processing capability of the eyes, and their highly advanced structure and function, certainly far exceeds the information speed that the serial mode of speech and the ears can offer.

Is a picture is worth a thousand words? Well, what information is conveyed when a picture is seen compared to when a thousand words are read? Images carry texture and form, and above all provide spatial relationships "at a glance". They present a whole world to which language can only allude. Inevitably, we must ask, how far can the advantages of light and image be taken?

**The Glass Bead Game**

The search for a universal language of visual symbols that can express the essence and subtleties of all knowledge has had a long and energetic history since Francis Bacon (1561-1626) suggested such a project [3]. One of the early proponents of universal visual languages was the brilliant and influential German philosopher Gottfried Wilhelm Leibniz (1646-1716) who envisioned a universal "character" that could express all knowledge and act as an instrument of discovery to uncover new concepts and truths. At the time, hints that a universal language might be possible came from the growing awareness of Chinese character writing, as well as the rediscovery of Egyptian hieroglyphic writing. The opening up of the Far East and the growing infatuation with Egyptian artifacts presented European scholars with a treasure of mind-expanding possibilities. There was an impression (albeit false) that the hieroglyphs represented things directly, and were divorced from the peculiarities of the spoken language. The existence of these forms of writing was cited as proof that a universal language was possible, which could impart ideas and concepts directly (visually) through written characters. The difficulty was in finding an efficient means to do this.

Leibniz outlined the goals of the project in his *Dissertatio de arte combinatoria* of 1666. Many of his activities related to the project, even his development of the calculus. He corresponded extensively with Johann Bernoulli, a co-inventor of the calculus, to discuss fine points of notation, striving to find the most consistent and efficient set of visual symbols to express the calculus. The standardized notation we use today for calculus was contributed almost exclusively by Leibniz, superseding the English physicist Isaac Newton's clumsy notation developed at the same time. But Leibniz was unable to find the time in a busy life to tackle the problem of a more general universal language. Others took up the call.

In the Twentieth Century, the psychologist Carl Jung strove for universality with his symbols of transformation [4], and in an altogether different sphere the English
logician and philosopher Bertrand Russell (1872-1970) and the English mathematician and logician Alfred North Whitehead (1861-1947) strove for the same thing with the symbolic logic they developed [5].

Yet the most imaginative picture of the potential of light and image was painted by the twentieth century Nobel Prize winning novelist Hermann Hesse (1877-1962). The novel Die Glasperlenspiel (The Glass Bead Game) was the last novel of the author and led to his receiving the Nobel prize in literature in 1946. Hermann Hesse was born in 1877 in the southern German town of Calw by the edge of the Black Forest on the Nagold river. As a young man he developed a voracious appetite for literature as he worked in bookshops in Tübingen and later in Basel, Switzerland. Always a loner and outsider, he immersed himself in his books and began a literary career. His first novel, published in 1904 when he was 27 years old, was Peter Camenzind. This novel brought the unknown writer rapid fame and won for him the Bauernfeld Prize of Vienna. He married Maria Bernoulli (of the famous mathematical Bernoulli family) the same year. The following years brought more literary success as Hesse explored the inner turmoil of his youth in his literature.

Hesse became acquainted with the theories of Carl Jung, which had a profound influence on Hesse's life and writing [6]. In particular, Hesse was fascinated by Jung's ideas concerning dreams and universal symbols. As more novels followed, including Demian, Siddhartha, Steppenwolf and The Journey to the East, Hesse's writing progressively looked inward with increasing emphasis on symbolism and vivid imagery. The culmination of his inward growth appeared in 1942, at the age of 65, with Das Glasperlenspiel (The Glass Bead Game).

The novel describes a utopian intellectual community called the Order that occupies itself with the study and playing of the Glass Bead Game. This monastic community exists in some future time, in a country named Castilia that is dedicated solely to the purposes of the Order and of the Game. The story of the Game, and in particular of Joseph Knecht, the Master of the Game, known as the Magister Ludi, unfolds through the narrative of a fictitious biographer.

The Game is an idealized version of the universal language envisioned by Leibniz. The narrator tells how the fictitious originator of the Game "...invented for the Glass Bead Game the principles of a new language, a language of symbols and formulas, in which mathematics and music played an equal part, so that it became possible to combine astronomical and musical formulas, to reduce mathematics and music to a common denominator [7]." Within this game, abstract concepts are represented by a set of glass beads, or icons. The visual and spatial arrangement of these beads by players allow all aspects of human knowledge to be related one to another: mathematics to art, music to astronomy, philosophy to architecture, and infinite combinations of these. The winner of the game was the player who succeeded in weaving the most striking or surprising connections and themes among seemingly disparate concepts. Though fanciful, the "Glass Bead Game" is a model for the visual representation of knowledge.

A quote from Leibniz in 1678, three centuries before, evokes the spirit of the Game: "The true method should furnish us with an Ariadne's thread, that is to say, with a certain sensible and palpable medium, which will guide the mind as do the lines drawn in geometry and the formulas for operations, which are laid down for the learner in arithmetic [8]." It is easy to imagine Leibniz as the Magister Ludi conducting a sublime
Glass Bead Game, the players forming threads of colored glass beads, this one representing a theorem of logic, that one an astronomical observation, and between them a musical theme branching to a mathematical formula, all interrelated, all sharing common forms that span the breadth of human knowledge condensed into symbols.

The importance of the Glass Bead Game is not the physical implementation of a set of rules that defines a game. In fact, Hesse was careful never to describe the actual rules by which the game was played. Furthermore, it must be admitted that universal language schemes (and there have been many [9]) all have failed by being too cumbersome and naive. However, the profound idea at the heart of the Glass Bead Game is that symbols and rules can be visual and that knowledge can be represented and manipulated visually. The Glass Bead Game is an allegory of a new optical language, the language of light and image needed to run the architecture of the future machines of light. This book explores those machines in which the language of the Glass Bead Game is about to become a reality.

**The Human Bottleneck**

The measure of any technology is the degree to which we live better by it. This may be posited as the principal thesis of technological humanism. One way that we live better is by reassigning human tasks to alternative agents. James Bailey, in his book *After Thought* [10], writes about successive stages of reassignment of human tasks. In the first stage we reassigned our muscle tasks to animals. Horses provided transportation, and oxen pulled our carts. The reassigned work remained on the scale of human effort — one man could drive a few horses. The revolution came after the second stage when we reassigned our muscle tasks to machines such as power engines and locomotives. This stage spurred the industrial revolution where the scale of the reassigned work extended far beyond human capability, and the change in society was irreversible. In the third stage we reassigned our mind tasks to calculators and computers where the increased scale has been mostly one of speed, rather than in ways of thinking. The fourth stage is set to begin when we succeed in reassigning our *conscious* tasks to our mental machines. The way these mental machines think will be the revolution, going beyond mere speed. Some of these machines will be visual.

A goal of early artificial vision systems was the detection of features in an image, such as straight edges in a photograph, or the detection of a unique character in a crowd — like finding the cartoon character named Waldo hidden amongst visual chaos in cartoon books. The machines that perform these image recognition tasks have drawn heavily on the mechanisms of human visual perception as a model of a working visual recognition system. As we see how these machines work, it is possible to envision where machines have a chance to go beyond human capabilities.

Our critical weakness in visual communication is the speed limit on comprehension as we read. The data structure of images allows us to see with speeds comparable to the data rate transferred from a computer hard drive; so why do we read so much more slowly than, say, a scanner can scan a page. For instance, you will spend about 2 minutes looking at this page of this book, while a laser scanner can scan it in a few seconds, and a digital camera can capture it in one-thousandth of a second.
Our limitations were created by evolution. The human brain has "co-evolved" side-by-side with the evolution of verbal communication. Despite the superior processing speed of the eye and vision over ear and hearing for receiving information, there is no exclusive biological optical equivalent to the vocal chords. We cannot send visual information to another person in a way that utilizes fully the data capacity of the eye. Sign language is certainly one way in which language can be sent visually. This is a highly efficient and expressive manner of communication, possessing favorable qualities that have no equivalent in spoken language. But one of the important findings of the past decades is that the speed of sign language transmission, even among its most adroit practitioners, remains comparable to the speed of spoken words.

The difficulty lies in a bottleneck — that of comprehension. Visual language, such as reading, starts out purely visually, as signs and symbols entering the eye and transmitted as parallel electrical impulses to the visual cortex. Once in the visual cortex, the neural impulses connect to the language comprehension centers of the brain -- centers that work primarily serially, a word (or a sentence fragment) at a time. In reading comprehension, the parallel processing by which a visual field of data can be perceived at once, as when we look at a picture, is not available. Visual language (writing, mathematical notation, music scores, sign language, etc.) has always required serial processing in the human mind. That is about to change.

BEYOND ANTHROPOCENTRICITY

Human limitations need not be machine limitations. There is no reason to believe that the specific manner in which we process language is the only possible way. We are free to try new things, to find new ways of interconnecting neurons and nodes in structures that are different from what nature has produced.

With technologies now becoming available we have an opportunity to explore and test alternative hypotheses concerning how intelligence functions. The way a system "thinks" reflects the architecture of the system, which is to say, different structures "think" in different ways. Rather than trying to make computers mimic the way we think, we should find different ways of thinking altogether.

Intelligent model building has already progressed through one stage — the reassignment of mind tasks to machines. This stage started with mechanical calculators, first implemented by the French mathematician Blaise Pascal (1623-1662) and Leibniz in the 17th century and by the English mathematician and inventor Charles Babbage (1791-1871) in the 19th century [11]. It continued with the greatly improved speed and accuracy of the first electronic calculators in the middle part of the 20th century. Yet today, our advanced computers remain exceedingly unintelligent, and are still far outstripped in reasoning by the human brain. What is currently demonstrated as artificial intelligence is mostly made possible by the tremendous and ever-increasing computing speed of modern day computers. The high-speed information processing abilities of computers make up for lack of insight. They get it right, but primarily by brute force.

Thus, this stage is not the revolution that some make it out to be. Mathematical computation is noticeably sped up by machines, but the calculations themselves remain the same as we would do by hand. The speed of solution has increased beyond human
capability, but the structure has not. The real revolution is beginning only now as the reassigned mind tasks evolve beyond human design by using adaptive and genetic algorithms that change their own structure in response to changing inputs, without human intervention. Such algorithms have the potential to evolve into intelligent systems with no human analog — possibly evolving beyond human comprehension.

Part of this revolution in intelligent model building is the current interest in artificial neural networks based loosely on the structures of biological systems. Scientists have analyzed how the functions of the brain are distributed over neurons, and are trying to translate those structures into electronic or photonic models. Networks of nodes and their interconnections mimic some of the structure of biological networks of neurons and their synapses. However, it is an open question whether mimicking the brain's structure is sufficient to produce an "intelligent" system. Biological model building is still in an early stage of development, with significant work ahead. Furthermore, basing intelligence on the biological neurological model may not be the best solution. Newer, nonbiological technologies (such as optical technology) may have more to offer.

Optical technology is primed to revolutionize intelligent model building. The advantage of the optical computer is its massive parallelism. For a digital computer, the unit of information is the binary unit, known as the "bit". For every tick of the internal clock only a handful of bits are processed even in the most advanced electronic computers. The bit does not carry much weight: only a "yes" or "no" answer. In some types of optical computer, on the other hand, the unit of information is an image. For every tick of the internal clock, the entire image, with all the information in it, is processed all at once. The parallelism of the image improves the data rate enormously.

If the single advantage of optical computers were in parallel processing, then it would still not be the revolution. Higher data rates may mean more computing power, but do not represent expanded function. Optical computers promise something more. They promise abstract and associative "reasoning" based on images and symbols which exist within a language of spatial and spectral (color) relationships. For an optical computer, a picture may well be worth more than a thousand words. A picture may be the program that tells the computer what functions it must perform and what concepts must be employed.

The rudimentary and specialized optical computers built so far in the laboratory [12] are not the flexible, programmable machines that will be able to make conjectures and leaps of imagination. Some of the current limitations have been in materials and in technology [13]. More importantly, a fundamental new architecture must be designed for the next-generation machines of light. The new architecture will need a new language in which to express itself. It must be an optical language where images are like words and the grammar is made up of visual projections and associations — we will need something akin to the language of the Glass Bead Game.

THE ARCHITECTURE OF LIGHT

Three basic ideas are crucial to understanding our own intelligence and how we can go beyond with the next-generation machines of light. First, all manner of human communication, whether audible through speaking and listening, whether visual through
writing and reading or the use of sign language by the deaf, or whether tactile through the use of Braille, share a common rate for comprehension that is limited by biological physiology. This is the Serial Comprehension Bottleneck. All communication channels must pass through the same cognitive centers of the brain to provide the ability to make informed decisions.

Second, images and words cannot be equivalent, even when considering the same written and spoken word, because the visual and auditory channels use different media that initially access different parts of the brain. Specifically, the visual channel is a massively parallel data channel that has unique attributes and advantages that far outstrip verbal and serial communication, if they can only be accessed. I call this the Parallel Advantage of Light and Image.

Third, and finally, the biological and physiological limitations underlying the human Serial Comprehension Bottleneck need not be machine limitations. We can build machines that can perform functions that we cannot. Speed alone is not such an advance. Rather, new machine architectures will utilize information in ways that go beyond human capabilities. This process of searching for new visual architectures based on a visual language of spatial and spectral relationships may allow machines to find new ways of thinking that utilize the Parallel Advantage of Light and Image. That new computational structure will be the Architecture of Light, the guiding principal that shapes the three generations of the machines of light.