



**A Survival Guide to Cope
with Information Explosion in the 21st Century:**

Picture-Based vs. Rule-Based Learning

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Abstract: This essay is more a dissertation on "examinology" than on "learning", let alone electrophysiology. The author, Felix Hong, suspects that many modern medical and premedical students work too hard and stay too focused in their studies in response to an information explosion and fierce competition. An alternative approach that is both efficient and effective in coping with this information explosion is presented, in what the author calls "picture-based" learning. The article attempts to explain why this approach works on the basis of cognitive science, artificial intelligence, and biocomputing. Thus, this important critique serves as both a new model for education, as well as a mandate to reexamine many of the cherished tenets of AI. -- Ed

Like most educators, I have taken for granted the conventional view of two modes of learning. The preferred mode is to understand the subject matter being studied. Rote memorization should be kept at a minimum and reserved only for those topics that are almost impossible to rationalize, such as one's own social security number or telephone number. As a veteran teacher, I am fully aware of the desirability to write examination questions that encourage thinking. Questions of simple recall type are to be used at a bare minimum and should be reserved only for those facts that we wish to ingrain firmly in the students' mind. It therefore came as a surprise to myself that there is yet a third mode of learning - something in between true understanding and rote memorization. For lack of a better terminology, I shall call it "rule-based learning."

Although I have long been intrigued by the topic of creative problem solving, my active involvement

in this area was fairly recently and almost totally unplanned. In fact, it was quite accidental and was the consequence of a "merger" of two unrelated activities of mine.

Like most contemporary scientific investigators, my research topic has almost always been separated from my teaching activity. I taught classical electrophysiology of nerve membranes for years. But my research was about electrophysiology of light-sensitive membranes - a different kind of electrophysiology that requires a different approach and different methodology. The latter topic is traditionally omitted in the standard curriculum of biomedical sciences. Having worked on bacteriorhodopsin membranes for almost two decades, I gradually strayed into molecular electronics and biocomputing. Being a relatively young discipline, biocomputing aims exclusively at machine intelligence rather than at human intelligence presently. However, it appears natural to extend biocomputing research to include creative problem solving and education. Thus, with an additional stretch of argument and through a tortuous big circle, the great divide between my research and my teaching is eventually bridged.

In 1995, I wrote an electrophysiology essay question for physiology graduate students who took a comprehensive examination at the end of their first year. I was astonished and disappointed by the outcome of the examination because only one out of ten students answered my question satisfactorily, in spite of my attempts to provide some hints in a review session about a week prior to the examination. I decided to try the same question again on a student after I provided additional hints. The student failed again and confessed that he really did not know *what I wanted*. However, I was convinced that my question was clearly written because at least one student gave a nearly perfect answer. After I eventually revealed the desired answer, the student said "Oh! I know the basic knowledge, but I just never linked it to the question you asked."

That evening I did nothing else but thinking about this incident. Why did the student who knew the materials fail to recognize the connection? Events like this have certainly happened to me before, but I usually dismissed the incident as a consequence of rote memorization. However, it was different this time. First, the student was known to be intellectually capable in other endeavors. Apparently, rote memorization was not the right explanation. Second, the incident took place at the time when I was working on an article about biocomputing for an encyclopedia. Confluence of these two unrelated factors led me onto a different path of thinking. Suddenly, my research on biocomputing and my teaching activity became "short-circuited" like a flash of spark touching off the two live wires inadvertently held too closely. I had abruptly come up with a working hypothesis (plausible but unsubstantiated explanation).

I asked the same student the next morning: "Did you learn electrophysiology by memorizing a set of rules and by mastering how to *manipulate the rules* in taking exams?" He said "Sure! That is the most efficient approach [in answering multiple choice questions]." As the student explained to me, what he did was simply match the question to a set of previously learned rules, identify the relevant rule to be used, and quickly find the correct answers from the provided choices. As I subsequently found out, some other students even went a step further by using a one-step procedure - identify the correct choice by simply matching the keywords. Apparently, saving time and effort was the primary driving force in determining these students' mode of learning.

The event reinforced a long-held suspicion of mine: the standardized multiple choice test was to blame. The student failed my essay question because my question demanded the ability to *generate new rules* from old knowledge. For rule-based learning to work, the rule being called for in an examination question must have already been included in the *repertoire* of previously acquired rules. Since standardized questions seldom require generation of new rules, rule-based learning works

satisfactorily most of the time. Surely, practitioners of rule-based learning can still "think," if they have previously acquired the necessary rules and have learned the correct procedure ("cookbook recipe") for manipulating the rules. Thinking is thus reduced to the practice of manipulating previously established rules according to some "canned" procedures. In this way, learning is relatively passive and requires minimal intellectual investment. Superficially, the practice is still *logical* thinking. However, it is certainly not *creative* or *independent* thinking because it was pre-programmed by the teacher or authority. [1] Pundits may argue that cleverly written multiple choice questions can still enforce independent thinking. However, in my opinion, learning to think by practicing on multiple choice questions is like learning to ride a bicycle with the training wheels permanently attached. Why? Because multiple choice questions often contain most of the clues or hints, whereas problem solving in real life requires active gathering of clues or hints. Besides, a student can only choose the answer from a limited number of possibilities, which are either false or previously known to be correct. The incurred thinking process bares little resemblance to creative problem solving.

If rule-based learning is so inadequate, what should the alternative be? What does *true* understanding mean if rule-based understanding is not? Literature about creative problem solving abounds. Imagination, intuition and divergent thinking are usually associated with creative problem solving. However, imagination, intuition and divergent thinking carry a mystical notion that these qualities seem to be part of innate ability rather than human traits that can be taught or learned. As shown in the psychoanalysis literature, free association is a powerful approach to dig up those deeply buried or repressed unconscious feelings and is certainly useful in creative problem solving. But does not a practitioner of rule-based learning also utilize free association to achieve a match between rules and test questions? What is sorely needed is a set of specific recommendations that can be followed by students. In other words, how can training enhance imagination, intuition and divergent thinking, if at all possible? Perhaps certain steps, if not all steps, in creative problem solving can be enhanced by training, especially those steps where habits are involved. Part of the answers is contained in the biographies of eminent scientists (especially physicists).

Albert Einstein was described to be highly visual in his scientific endeavors. His celebrated *gedanken experiments* demand audience participation in the form of "visualization" of fictional scenarios. Richard Feynman solved difficult physics problems by utilizing "Feynman diagrams." Stephen Hawking also described himself as being visual in his approach to profound cosmology problems. The much-valued ability of *abstract thinking* in science actually demands *concrete visualization* in terms of diagrams of representation. The history of mathematics offers a display of the human being's incessant desire to abstract (or rather, extract) rules from concrete pictures exhibited by natural phenomena. Moreover, the same set of rules often *represents* a wide variety of superficially unrelated phenomena. Thus, the preferred antidote to the practice of rule-based learning is what I call "picture-based learning" or "picture-based reasoning." What is wrong about rule-based learning is not the use of rules in reasoning but rather the practice of complete separation of rules from pictures.

Although it is most convenient to use real life examples to illustrate picture-based reasoning or learning, an explicit definition seems desirable, and a number of individuals who have heard my view have demanded it. Of course, picture-based reasoning relies on visualized pictures or diagrams in reasoning. The visualized picture may be a real and concrete picture. Or, it may be a somewhat "fictionalized" picture like atomic orbitals. Or, it may be a conceptual diagram that extracts the essence of an event in abstract terms, such as the reaction coordinate diagram of the transition state theory and the "peak and valley" landscape in evolutionary processes. Or, it may be a mental picture based on analogy or similarity of the mathematical equations. In this way, one resorts to what is known in mathematics as *homomorphism*.

For example, in explaining the electrical processes of nerve phenomena when I teach electrophysiology, I routinely resort to the homomorphism between the behavior of a resistor-capacitor (RC) electrical network under the action of a battery and that of a water reservoir (capacitor) with a small drain pipe (resistor) under the action of a water pump attached to the bottom of the reservoir. The two superficially unrelated physical phenomena behave according to the same mathematical equations. Originally, I was motivated to this practice of teaching by means of analogy because of the ever-declining mathematical proficiency of medical students. I used the hydraulic analogy merely to side step the unpopular practice of solving a first order differential equation. Thus, a less familiar and psychologically more intimidating phenomenon (electricity) is transformed into a user-friendlier phenomenon (water flow) encountered in our daily life. [2]

Picture-based reasoning may take the form of a metaphor, like referring to the response of a dictator to criticism in terms of a physiological (and engineering) concept of positive feedback (a dictator quenches criticism by throwing dissidents in jail or executing them, thus becoming even more oppressive), or referring to the "customers-are-always-right" approach in business in terms of a similar concept of negative feedback (answering a customer criticism by giving them what they want). [3] The more general form of picture-based reasoning is thus heavily tainted with rule-based reasoning (homomorphism of different kinds or levels of rules). In fact, purely picture-based reasoning is rare and almost impossible. Many of us biologists accept rules from physics and chemistry without questioning the validity or fully understanding them, but use them to construct picture-based reasoning in biology any way.

From the above definition, picture-based reasoning demands representation of events or phenomena by concrete diagrams, and the ability to process these diagrams by means of *pattern recognition*. In contrast, rule-based learning represents events or phenomena in terms of rules that can be enunciated by spoken or written languages in a sequential fashion. Thus, in a typical lecture, the instructor uses spoken words to present the rules but uses audiovisual aids to convey the entire pattern ("big picture"). Rules and pictures are inseparable in a typical and traditional lecture. However, that does not mean students will assimilate both rules and pictures equally. It is conceivable that a student, when under great time pressure and/or great pressure to achieve, is tempted to retain the rules and ignore the pictures. As a consequence, the rules so learned become somewhat abstract and devoid of concrete meaning. It is obvious that picture-based reasoning often takes the form of "parallel processing," whereas rule-based reasoning primarily takes the form of "sequential processing." Thus, rule-based reasoning is similar to the operating principle of expert systems, which was developed in the early stage of artificial intelligence (AI) research, whereas picture-based reasoning is akin to neural network operation that was launched as a counterculture to traditional AI. From cognitive science's point of view, rule-based reasoning comes close to what the left cerebral hemisphere does, whereas picture-based reasoning is what the right cerebral hemisphere does best.

Unfortunately, giving definitions without providing real examples is itself an attempt to enforce rule-based learning because definitions are rules by themselves. Therefore, I could not resist the temptation to explain my view with some real life examples. Such pertinent examples allow for establishing representing or representative "mental pictures" about picture-based reasoning itself.

As a teenager, I had plenty of free time to engage in personal endeavors and hobbies because I was lucky to have narrowly escaped the assault of a subsequent wave of immense pressure for high school students to succeed academically; success became measured solely by being admitted to one of a small number of elite colleges. Therefore, I even had time to read "trash" novels in my spare time.

I once read a mystery novel, the title of which I have since forgot. Nor do I remember the plot. But one event sticks firmly to my mind. The detective in the story scored an important breakthrough and he was able to nail the murderer. Initially, the detective was searching for a piece of hard evidence (a strand of hair or something like that), but got nowhere after combing the carpet at the crime scene. One day, a stroke of inspiration hit the detective. He decided to check the alleged murderer's trouser cuff, which was recovered at the crime scene. He found what he had wanted right there. Apparently, while falling down, the piece of evidence had been trapped by the cuff before it hit the floor. I was so impressed with that discovery that it became the only part of the plot I remember almost forever.

A couple of decades later, I inadvertently dropped a tiny but hard-to-replace screw. I began a frustrating search on the floor in vain. Then, I recalled the story line of that mystery novel, and I checked my trouser cuff and found it right there.

The incident repeated itself again several years later. Only this time, I wore a pair of trousers without a cuff. Here is how picture-based reasoning could make a difference. I would not have been able find anything had I simply followed the rule: check the trouser cuff when you drop something to the floor. Picture-based reasoning helped me formulate the notion of a "trap" - something that can trap an object while it is in the process of falling to the ground. [4]

Although the example I present above is trivial, conceptualization often is formulated by means of picture-based reasoning. The simple conceptualization process, which is based on the shape and a "latent" function of a trouser cuff, [5] leads to a *generalization* that includes pockets of my lab coat, where I found the dropped object instead. This simple conceptualization is certainly not an extraordinary intellectual feat, but the *habit* of making such attempts every time opportunity arises can make a big difference in solving more serious problems. Several times in my own research I managed to see clues that eluded most of my fellow investigators, who were better trained than I. I owed my advantage to the practice of picture-based reasoning. This trait (actually a habit) is commonly referred to as having a good physical intuition. I believe that picture-based reasoning is a better description than intuition itself because the notion of intuition mystifies the accompanying mental process, whereas picture-based reasoning depicts the process explicitly and makes it possible and feasible to acquire that trait by conscious practices. I do not think the only way to acquire good intuition is to pick the right parents, although I cannot prove it. [6]

As another example, let us consider the following problem. A lotus growing in a pond doubles its surface coverage every 24 hours. If it takes 60 days for the lotus leaves to cover the entire pond, how long does it take for lotus leaves to cover 50% of the pond surface? Picture-based reasoning allows one to answer this question in a fraction of a second. All one need to do is visualize a growing coverage as in a movie. In order to get the answer, one need only run the movie backward and consider the "half life" instead of the "doubling" time by pushing the entire period of 60 days back one full day to get 59 days.

Surely, one can solve the above problem by rule-based reasoning. Get a piece of paper and a pencil ready, write down the first order ordinary differential equation, and solve it. Solving this differential equation probably takes 5 minutes if one still remembers the rule so many years after schooling: the (first) derivative of an exponential function is the same exponential function. Otherwise, it may take somewhat longer, depending whether one has a book of mathematical tables handy. Or better still, if one is in the business of solving differential equations on a daily basis, one may recognize that it is exactly the same problem as population growth and the answer is well known - an exponential growth curve [not decay curve] and the doubling time [not half life] is 24 hours. The answer will

come out in approximately 1-2 minutes. Please note that the second approach is half picture-based and half-rule-based reasoning because one must first recognize the same pattern shared by population growth and lotus growth - the recognition requires picture-based reasoning.

The above examples highlight several important points about reasoning. First, picture-based reasoning is intimately related to conceptualization and generalization. In doing so, one relies heavily on analogy. [7] Analogy is best implemented through pictures, although not exclusively so. Therefore, there is a heavy component of pattern recognition and parallel processing - recognition of the underlying analogy. Picture-based reasoning thus constitutes what Gestalt psychologists frequently preach - Gestalt synthesis (*Gestalt* means "form" in German). On the other hand, rule-based reasoning is more precise, and better defined and straightforward and easy to verbalize. Rules usually are concise statements of lengthy reasoning or even crystallization of somebody else's lifetime work. Strictly speaking, concepts are rules. Recipes (including the real ones enunciated by reputed cooks such as Julia Child) are condensed forms of reasoning and wisdom. Direct uses of rules and concepts save time. This may be why modern medical and premed students are forced or lured into the practice of purely rule-based reasoning long before students of other disciplines become similarly infected. I believe this new trend has a lot to do with the information explosion and increasingly fierce competition (arguments in support of this conclusion are omitted here). At the very least, these two factors explain why there is a high incidence of this malady among our own medical or premed students. Thus, saving time is apparently an important strategy for student survival when the pressure to succeed is mounting and when time becomes a premium. The problem is: Is rule-based learning really timesaving, especially in the long run?

No, rule-based reasoning does not always save time. As the second example above has illustrated, recognition of a similar pattern in an entirely different problem (lotus growth vs. population growth) allows one to cut through the tedium of having to solve the same differential equation over and over again, and quickly get right to the answer. This is especially so if the recognition and transfer of rules (imitation) are done across the boundary of disciplines. Recently, I refereed a scientific paper that applied finite elemental analysis to a problem of electrode design for drug delivery (by means of electroporation) in cancer therapy. It appears quite innovative in biology, but finite elemental analysis has been around in engineering practices even before cheap and fast computers became available to individual investigators. Finite element analysis is such a common place in engineering that I have even seen it featured in a TV commercial from one of the "Big Three" automakers. [8] Thus, by drawing inspiration or hints from resources and discoveries made in other disciplines, picture-based reasoning prevents "reinvention of the wheel."

Ironically, the most extreme form of rule-based reasoning in the classroom also relies on "pattern recognition": recognition of *key words*. It is an efficient approach in handling a large number of multiple choice questions. However, it is a very serious educational problem because a real life problem seldom presents itself with a combination of correct and commonly known key words. [9]

There are several consequences that I have observed as a teacher and as a course director of a team-taught course.

A direct consequence of rule-based learning to the students is their having to learn the same materials over and over again, including as many times as possible variations or disguises the same question can assume. A mere rephrasing of the same question and/or a change of test format may throw the students completely in the dark. This is why students are so voracious in reading old examinations. [10] This is also why students have to work so hard (the information explosion is not the only reason) because they must study the same problem in different (all possible) formats of variations and

disguises.

Interestingly, in a neural network designed for face recognition, the systems performance improved dramatically by merely suggesting to the artificial neural network program that there is a left-right symmetry of a human face.[\[11\]](#) By way of crude analogy, students who resort to purely rule-based learning must memorize not only the left and the right sides of a face, but also more views from many intermediate angles, and then must independently store all these views as separate "templates" for future retrieval when the need to recognize the face arises. Although this analogy is absurd, the absurdity of the implied approach is quite apparent.

Because of the unnecessary duplication of efforts, students naturally have no time left to think because of the unnecessary duplication of effort. Without adequate thinking, they are forced to dig deeper and deeper into the practice of rule-based learning, leaving them even less time for thinking. And there you go again with a vicious cycle (positive feedback process). The pity was: lack of picture-based reasoning might have prevented some students from recognizing the fact that they were being trapped in the misery of a vicious cycle.

Students who took my advice and started the practice of picture-based reasoning reported back to me that picture-based learning is not really more time consuming. It is true that picture-based learning requires an initial capital outlay in the form of extra time needed to assemble the pictures and to explore the subject from different angles. But once done, the acquired knowledge is retained much longer ("almost impossible to forget!"). Thus, picture-based learning saves time in the long run. In contrast, the short retention of knowledge acquired by means of rule-based learning forces students to "cram" their study into the last few days or even the last few hours prior to an exam. In view of ever-accelerating information explosion, rule-based learning leads to a dilemma. If one starts too early to prepare for the exam one may not remember by the time of exam. If one starts too late one runs out of time, instead. [\[12\]](#) Rule-based learning thus defeats the primary purpose of education - retention of knowledge for future uses.

Another problem of rule-based learning is that the practice gives a student a false sense of understanding, as the following example demonstrates. A freshman medical student came to me after attending a session of my lectures on electrophysiology. She told me that she had previously taken a physiology course elsewhere in a highly reputed medical school and had successfully handled a mock Medical Board Examination. She felt totally lost in my lecture but insisted that she understood electrophysiology. I therefore gave her a simple test about a well-known topic in electrophysiology (and electrochemistry): Nernst potential. The Nernst potential in an electrical voltage in a nerve membrane that arises from unequal distributions of an ion such as potassium across the two sides of the nerve membrane, through which only that particular ion can go via tiny ion channels (literally holes through the membrane). My question is: a 10 to 1 ratio of potassium ion distributions across the membrane ("ionic gradient across the membrane") gives rise to a potassium Nernst potential of -61 mV at body temperature whereas the same ratio of calcium ion distribution leads to a calcium Nernst potential of -30.5 mV, instead. Why?

She answered "because the Nernst equation requires the computed calcium Nernst potential to be divided by 2." I asked why again. She said, "because a calcium ion carries 2 positive charges instead of one as in a potassium ion." I asked why again a third time. Why? Why? Why? - Like a string of endless questions from an innocent child. Why not multiply by 2, or divided by the square root of 2, etc.? Aren't there a zillion ways to manipulate the number 2?

The student finally admitted, "I really don't know why." Thus, understanding in rule-based learning is

somewhat superficial and relies on others' judgment for its validity ("because the textbook said so!"). While rule-based reasoning usually satisfies the requirements of logical reasoning, rule-based learning eventually undermines logical reasoning; persistent reliance on others' judgment eventually eliminates one's ability to judge. This is why our students often present ridiculous and absurd arguments in their answers to essay questions without realizing their logic flaws. They have no way of knowing for sure whether the arguments are valid other than just giving it a try and let the teacher decide.[\[13\]](#)

I then spent the next fifteen minutes explaining the *picture* behind the mathematical derivation of the Nernst equation *without* writing a single mathematical equation.[\[14\]](#) She had no difficulty following my reasoning, and admitted that it wasn't hard, and wasn't time-consuming either. I further convinced her that learning the Nernst equation via diagrams is a lot more reliable than merely memorizing the equation. This is because the Nernst potential carries either a plus or minus sign, which depends on the sign of the charge carried by the ion (plus for potassium ion and minus for chloride ion) as well as the "sense" of ratio of ion distribution across the nerve membrane (a regime with a 1 to 10 ratio gives rise to a sign opposite to that of a regime with a 10 to 1 ratio). Thus, a single mistake in memorization leads to the wrong sign, and two mistakes compensate each other and gives rise to the correct answer. Topics like that are potentially confusing if one relies solely on memorization. With some practices, my fifteen-minute verbal rendition of picture-based reasoning can be executed in less than five seconds quietly in one's own mind. It is foolproof but not really time-consuming. The understanding is also deeper.



Thus, picture-based learning relieves the burden of having to memorize many rules that can be derived *de novo* or "re-discovered" in a reasonably short time. The time saved can then be diverted to study of other subjects for which rote memorization is a demanded premium, such as anatomy.[\[15\]](#)

Rules are usually made by others, especially by those who are good at picture-based reasoning. The wisdom associated with the rules usually gets distorted or lost during the information transfer (teaching of the rules). Therefore, another big draw back of strictly rule-based learning is misuses of the rules for lack of fully understanding the wisdom behind the rules, or abuses of the rules for lack of fully recognizing the limitation of the rules.[\[16\]](#) This conclusion applies not only to science but also to real life situations in terms of regulations or laws, as the two following examples will illustrate.

I once took a newly arrived graduate student from a foreign country by car around Detroit to help him settle down. I stopped at a red light at a not-so-busy intersection. Seeing neither cars nor cops around, the student asked me: "Can't you just go through the red light?" I replied, "Yes, you can. The police won't know unless somebody reports you or you turn yourself in. But if you develop the habit of jumping a red light, someday you may get killed in a car accident." I guess nobody had ever told this student that traffic rules were designed for his own safety.

As a second example, a freshman medical student challenged one of my examination questions for its validity. The question was about how a change of the sodium ion distribution across the nerve membrane can affect the amplitude of an action potential (the size of a nerve impulse). The objection of the student was based on a well-known and well-publicized rule called "all or none principle,"

which states that if the stimulus to a nerve is intense enough to excite the membrane a full-fledged nerve impulse (with full size) appears; whereas if the stimulus is inadequate, no nerve impulse emerges (a weaker stimulus does not lead to a smaller nerve impulse); sort of like "winners take all" in a U.S. presidential election by the electoral college voting. The student forgot the rule applies to a situation where the only factor that is stipulated to change is the stimulus intensity, while implicitly the ionic distribution across the nerve membrane are held unchanged. It worried me a lot; not because the student did not learn enough electrophysiology; but because the same mode of reasoning may cause a patient to die prematurely and unnecessarily in the future.

While I was developing my "view" about rule-based vs. picture-based thinking, I often brought up the topic at cocktail time. Some colleagues questioned the validity of my view presumably because my "success" cases are anecdotal (based on a small number of subjective observations) and/or because I was not trained in education (few, if any, college professors are graduates of a college of education). It is therefore my obligation here to demonstrate the scientific basis of my view. I will highlight the scientific basis in three disciplines: cognitive science, artificial intelligence and biocomputing. A more detailed, more rigorous and perhaps more scholarly exposition will be published elsewhere.

Here, I must point out that traditional research in education relies on psychology and cognitive science whereas machine intelligence research belongs to the realm of engineering and computer science. Biocomputing is a relatively young discipline that can be described as a hybrid of cognitive science and computer science and engineering, and may offer some new insight into education. Curiously, biocomputing primarily aims at machine intelligence, and the author's attempt to include education as part of the goal has already elicited some protests from several colleagues in the name of maintaining focus in a given discipline ("If you include everything in biocomputing, you don't have a [research] field."; perhaps it means that the membership in a research field should be made somewhat exclusive.). The author's view remains relatively untested and therefore must be regarded as unproved. However, by now it is obvious that repeated attempts for educational reform, made since the 1983 appearance of the famed document "A Nation at Risk,"[\[17\]](#) were not working satisfactorily. In my opinion, it was getting worse over the last two decades based on my "anecdotal" and somewhat subjective observations. My approach to instigate picture-based learning apparently has worked for those students who were willing to try. I am thus eager to share my views and to make them available to those students who are willing to take a risk and try it out. If one suspects a reason why a house has been repeatedly on fire, it seems to me very foolish to ignore the suspicion until a large number of repetitions eventually permits a valid statistical analysis.

From the point of view of computer science, it is quite apparent that the two modes of reasoning, rule-based vs. picture-based reasoning, are intimately related to a major issue in artificial intelligence: pattern recognition and machine vision. A linear sequential algorithm in digital computing is similar to rule-based reasoning. It comes as no surprise that rule-based reasoning is most suitably developed in an environment of digital computing because it is easy to program the rules by means of a linear program in a step-by-step fashion. The decision making steps are implemented as "conditional jumps" in a branching linear program, e.g., "if then ... else". Rules are usually made in such a way that the dichotomy of "yes" or "no" can be handled by the very digital nature of not admitting any signals unless the signal is either a "1" or "0" (typically, in hardware, a "5 volt" or a "0 volt" signal). A number of early AI expert systems were so successful in part because problems that are amenable to rule-based reasoning were preferentially selected for implementation. But medical expert systems failed to put physicians out of job because physical diagnosis is still partly science and partly art (requiring an overall judgment based on conflicting information).

The existence of conflicting rules in digital programming is considered a program "bug." Resolving mutually conflicting rules requires an ability tantamount to political wisdom. Thus, digital computing or linear sequential programming is utterly incompatible with a political or esthetic judgment because the latter requires judgment as a whole and assigning appropriate (desirable) weights to conflicting factors. By the same token, digital computing is ill suited for implementing the capability of pattern recognition. Almost by definition, pattern recognition requires judgment on the pattern as a whole. This is in part because pattern recognition requires matching patterns that are *not exactly identical*, in size, in shape, in spatial orientation, and often in *disguised* appearance. Pattern recognition demands only a crude match of "shape" and in fact *requires* a crude match. In other words, pattern recognition requires the ability to distort and stretch the "template" before making the match. Pattern recognition relies on the ability to distinguish between *essence* and *triviality*, or rather, between *signals* and *noises*. Digital computing cannot tolerate "imperfections." Yet tolerance to "imperfections" is the key to pattern recognition much like "compromise" is the key to political wisdom. In short, digital processing has little natural affinity for pattern recognition, much less value judgment.

Informed readers in computer technology will certainly object to my rather "rigid" and harsh indictment of digital computing. They will cite the emergence of "fuzzy logic," and neural network processing as counter-examples to my claim. The points are well taken, and I certainly should make a more "flexible" interpretation instead. Both "fuzzy logic" and neural network processing have been successfully implemented in the environment of digital computing. But digital computing is not a natural environment either for "fuzzy logic" or "pattern recognition." Computer scientists and engineers have to create a *virtual* environment within the digital environment, and to create a *virtual machine* within a *real* digital machine. This implementation has often incurred an enormous *software overhead* because of the need to emulate a virtual machine in a digital machine. [18] However, increased memory size and the enhanced speed of modern digital computers make such emulation possible. But it is neither as efficient nor as flexible as computer experts have wanted and/or real life problems have demanded. This is one of the reasons why scientists and engineers are trying to find an alternative approach by seeking inspiration in biology, thereby leading to the birth of a new discipline - molecular electronics. But this field is still in its infancy.

On the other hand, neural network processing is more flexible in processing pattern recognition or in decision making under ambiguous conditions. The kind of catastrophe usually associated with programming "bugs" is minimized or eliminated in part because information processing is distributed among many "synapses" in the artificial neural network. A neural network program can be trained and can learn with or without supervision. A training session sometimes involves presentation of a large number of examples to serve as representative patterns or pictures.

The above reference to artificial neural network computing does by no means imply that real neural network computing (i.e., brain function) resorts only to picture-based programming. In fact, cerebral lateralization led to the segregation of the two modes of information processing: for a naturally right-handed person, the right cerebral hemisphere is critical for the *exploratory* processing of novel cognitive situations whereas the left hemisphere is critical for information processing based on pre-existing representations and *routinized* cognitive strategies. Here, I use the more modern interpretation proposed by Elkhonon Goldberg of New York University and his colleagues. The traditional verbal/nonverbal dichotomy of cerebral lateralization thus becomes a special case. Goldberg's view can be rephrased in our present terminology: the left cerebral hemisphere is specialized in rule-based reasoning, whereas the right hemisphere is specialized in picture-based reasoning. Our interpretation is also consistent with the conventional view that the left hemisphere is logical and the right hemisphere is intuitive. Intuition is associated with the uncanny ability to find

unlikely but correct solutions and the inclination toward exploration - divergent thinking. Imperfect matching of patterns is essential in exploration of novel cognitive processes. Visual patterns are to be judged as a whole (Gestalt synthesis, see above). [19] It is thus obvious that the right hemispheric function is primarily picture-based reasoning or pattern-based reasoning and is therefore nonverbal in nature. On the other hand, rule-based reasoning, as in logical reasoning, is most suitably carried out in verbal terms and requires precisely implemented step-by-step sequential processing. This was why early expert systems selected topics that were heavily rule-based.

Thus, in cognitive terms, our premed and medical students have increasingly levitated towards the use of their left brain at the expense of their right brain. In artificial intelligence terms, our premed and medical students have been trained like an expert system (or "robot"), and education is reduced to the fabrication of examination-taking machines. But, unlike the digital computer-based expert systems, our students lack the vast data base, the high speed, the unfailing accuracy and extraordinary stamina of a good expert system -- not to mention that they are expensive to make. Furthermore, examination-taking machines quickly become obsolete because of information explosion. While the first round of expert system uprisings failed to put physicians out of jobs, the outcome of repeated assaults from future generations of artificial intelligence remains to be seen.

A lingering question remains. Why does the human brain resort to both rule-based and picture-based reasoning? Clearly, rule-based reasoning must have some survival values despite my misgivings mentioned above. I have looked into the problem and, through introspection, I propose the following explanation. In solving a problem, the human brain needs to examine a large number of possible solutions before arriving at a workable one (what cognitive scientists refer to as "search space"). The accompanying information processing is handled in short-term (working) memory. But short-term memory fades quickly. It is therefore advantageous to utilize rules or concepts ("compressed" or "zipped" information) in order to score a quick match between the problem and one of the solutions. The ability to search available *options* at high speed enables one to search for more options within a given time (larger *search space*). Slow searching makes the process ineffective because the working memory cannot hold the temporarily stored options forever for a delayed comparison or delayed processing. Thus, one big advantage of rule-based reasoning is speed and efficiency in solution searching. But is it also effective?

Exclusive rule-based reasoning is not effective because it lacks the exploratory nature of picture-based reasoning. A big drawback of strictly rule-based reasoning is its inability to cope with a *novel* situation or *novel* problem. An important phase in creative problem solving is searching for possible matches between a problem and available solutions. Picture-based reasoning allows for a bigger search space by recognizing the analogy between superficially unrelated phenomena, of which the subtle analogy may escape detection by purely rule-based reasoning. Alternatively, given the same size of search space, picture-based reasoning allows for detection of matches that eludes those who practice rule-based reasoning exclusively. [20] Thus, picture-based reasoning is effectively increasing the search space by looking into areas that would otherwise be neglected or effectively enhances the ability to recognize solutions that are normally ignored.

Rule-based reasoning serves yet another important function. French mathematician Henri Poincare once said " ... it is by logic that we prove. It is by intuition that we discover." Because false matches by picture-based reasoning are not uncommon, subsequent verification is necessary. Verification is usually performed in terms of logical reasoning which applies well-established rules in a sequential and rigorous fashion; a crude match cannot be tolerated. As pointed out above, misuses or abuses of rules are likely because condensed knowledge gives scanty clues about its range of validity. It is often necessary to "decompress" or "unzip" the condensed rules or concepts in the step of

verification. [21] Persons who practice exclusively rule-based reasoning are less likely to remember or even pay attention to the detail of "decompressed" or "unzipped" knowledge or the reasons leading to formulation of rules. Thus, practitioners of purely rule-based reasoning often suffer from misuse or abuses of rules (see examples above).

While properly executed rule-based reasoning constitutes a form of thinking - logical reasoning, exclusive uses of rule-based reasoning or learning present a slippery slope. When pressured by time, knowledge about the reasons behind the rules becomes a luxury. Pretty soon, judgment by authority becomes the sole criterion of validity. Habituation eventually "desensitizes" an individual to the point that one really cannot care less about the validity of rules. [22] Thus, logical reasoning become quickly transformed into a guessing game. Rule-based learning thus disintegrates into pure rote memorization. [23]

Some concerned teachers often point out the declining proficiency of mathematics among American students as a major factor contributing to their inability to think *logically*. Superficially, this is a plausible cause because mathematics (especially geometry) provides an excellent training ground for logical thinking for many of us. Although there may be some truth in this assertion, the problem goes deeper than that. In fact, many individuals trained in humanity and social sciences became superb thinkers, apparently without much help from training in mathematics. On the other hand, training in mathematics does not guarantee the ability to think creatively or logically.

I accidentally found that some engineers, though amply trained in mathematical manipulation, knew only the mathematical rules (procedures) without knowing the reasons underlying the procedures. Mathematics is just a black box into which one plugs in the parameters, and canned procedures bring out the solution automatically. [24] This was probably the consequence of American pragmatism. American students often say that "hands-on practice is cool, but theory is nerdy." It seems to me that a significant fraction of mathematics-literate Americans know the mathematical rules but lack an intuitive feeling about the subject matter. Again, this was a consequence of rule-based learning. This is also analogous to the following situation. Those who are accustomed to using a calculator but are not familiar with long hand calculation eventually lose the intuitive feeling about numbers and become insensitive to blatant arithmetic errors at a supermarket checkout lane.

On the other hand, because of the tendency for students to disregard the reasoning behind mathematical rules, I usually view reports of superior performance in mathematics and science by Asian students with some reservation and skepticism because that type of reports were often based on standardized tests. However, a total denial to the warning about the decline in the performance of American students as compared to their Asian counterparts will almost certainly postpone a timely solution until it becomes too late.

As a closing remark, I now routinely preface my teaching with equal emphasis on rule-based and picture-based learning. [25] Since rule-based learning needs no incentives from the teachers' encouragement, I usually take pains to explain the shortcomings of exclusive rule-based learning. First, picture-based learning ties superficially different but fundamentally similar phenomena together, making information storage more organized and information retrieval more feasible and efficient, and thus effectively averts premature information overflow and overload. Second, picture-based learning facilitates retention of information over a prolonged period. Third, picture-based learning is less time-consuming in the long run because it eliminates the need to learn similar and related phenomena or mechanisms over and over again separately as individual and unrelated modules of knowledge. It also eliminates the need to memorize certain subjects or formulas if one can reconstruct the knowledge or derive the formula quickly at a moment's notice. Fourth, picture-

based learning fosters innovation because of its inherent exploratory nature and of its inherent affinity for recognizing novel solutions. Picture-based reasoning provides a natural environment to implement what psychologists and psychiatrists refer to as "*free association*", and free association is essentially a mental linkage of superficially dissimilar but fundamentally related "pictures" or "patterns." Picture-based reasoning makes one more creative by recognizing solutions that eluded others by virtue of the enhanced ability to make an imperfect or subtle match of patterns. Fifth, picture-based reasoning strengthens logical reasoning because of an enhanced feeling about the reasoning behind the formulation of rules, and thus averts misuses or abuses of rules and the uses of pseudo-logic.

Last but not least, rule-based learning gives a student the false sense of understanding and a loss of child-like innocence that was vividly illustrated by the fabled declaration: "The Emperor has no clothes on!". The accompanied lack of exploratory instinct eliminates the most treasured asset of human mind - *curiosity*. Picture-based reasoning fosters mental agility whereas exclusive rule-based reasoning leads to mental rigidity and dogmatism.[26] While it is apparent that exclusively rule-based learning in medical education will almost certainly cause health care expenses to rise sharply and health care quality to decline in the 21st century, there is a far more serious implication: a proliferation of exclusively rule-based learning to other disciplines in addition to biomedical sciences may eventually lead to the decline of civilization.

This article is dedicated to the memory of the late President Detlev W. Bronk of The Rockefeller University, who insisted that a scientist must not only be well trained but also be well educated.

[1] Animal behavior scientists have presented evidence that a chimpanzee is capable of creative thinking (for example, see "Animal Minds" by D. R. Griffin, University of Chicago Press, Chicago and London, 1992). In contrast, a robot or an expert system does not really think creatively because it follows the rules laid out in terms of hardware and software by the designer/programmer, and follows them with unflinching precision. In other words, an expert system was preprogrammed and controlled by a Svengali behind the scene even though Svengali himself could not perform as well.

[2] This type of analogy helps students who lack engineering or physics background. Medical students used to express their appreciation for my effort. Lately, some medical students felt insulted by my use of the hydraulic analogy. They protested "Don't bother using the analogy. We can take HARD SCIENCE." There are at least two possible explanations. First, I suspect that some students did not even know the physics of hydraulics: an unfamiliar analogy is a useless one. Second, practitioners of rule-based learning resented analogy because the use of analogy inevitably inflates the amount of information being transferred.

[3] Real life behavior of a dictator is homomorphic to the "picture" of balancing a ball at a seal's nose tip. A slight push of the ball away from the balancing position causes the ball to become further off balance (the incurred force pushes it away from the optimal balancing position.). Thus, a positive feedback process is tantamount to a vicious cycle in the conventional sense. On the other hand, the behavior of a businessman eager to please the customers is homomorphic to the "picture" of balancing a ball at the bottom of a U-shaped well. Any attempt to push the ball away from the optimal balancing position generates a restoring force to bring the ball back to its original balancing position. Thus, the "peak and valley" diagram mentioned above can also be used to illustrate the concept of positive feedback and negative feedback.

[4] According to rule-based reasoning, if I drop a basketball down a cliff but cannot find it at the foot of the hill, I should check my trouser cuff. But according to the "trap" concept formulated by means of picture-based reasoning, I should check the branches of trees growing halfway up the cliff instead.

[5] Catching a falling object was not the original purpose of designing a trouser cuff. In bioelectronics, a "latent" function such as color changes upon illumination of bacteriorhodopsin serves no known physiological purposes but can be recruited for making devices. Please see the article "Bacteriorhodopsin as an intelligent material: a nontechnical summary" in a 21st back issue.

[6] Intuition is an elusive character trait that psychologists found hard to define (see T. Bastick, *Intuition: How We Think and Act*, John Wiley & Sons, 1982). It seems that picture-based reasoning can foster intuition. Of course, intuition is more than that. Intuition (as well as divergent thinking) also demands the ability to generalize, and to recognize subtle similarity in patterns, and perhaps much much more. Since enhancement in some of these steps can be made by conscious practice of picture-based reasoning, I suspect intuition is not exactly an innate ability.

[7] Mathematical homomorphism relies heavily on analogy but demands quantitative accuracy and axiomatic consistency (please ignore this remark if you find it too "rule-based.").

[8] Of course, the ad did not mention finite element analysis, but the telltale picture of "grids" on a car's body betrayed just that.

[9] As a real life example, my daughter once visited a local HMO medical center because of swelling of an injured joint but without an open wound. In describing the symptoms, she incorrectly used the key word "infection" instead of "inflammation." The physician prescribed antibiotics even though apparently no microbes were involved in the ailment. I suspect the use of key word "inflammation" instead might have triggered a different prescription such as aspirin or other anti-inflammatory agents.

[10] According to an article in *Science*, November 1, 1996 (Vol. 274, p. 710), prior exposure to multiple choice questions could account for a margin as large as 200 points in GRE scores (possible scores ranging from 200 to 900).

[11] Y. S. Al-Mostafa, 1995, *Machines that Learn from Hints*, *Scientific American*, Vol. 272, No. 4, pp. 64-69 (1995).

[12] Some of our colleagues present their lecture notes on the Internet. Sure enough, in a recent examination, the Internet line was jammed and clogged the day before examination.

[13] I had the following experience in a small group discussion session. Students attempted to guess the correct (logical) answer to an essay question, and the instructor had to judge truth or fallacy. Ironically, a small group discussion turned into a multiple-choice exam in reverse: the students offered choices of answers and the instructor was required to select from them.

[14] I once participated in an education workshop held in SUNY buffalo campus. Each participant was asked to give a fifteen minute lecture and the rest of participants was asked to critique the lecture. I selected the topic of Nernst potential, and a professor specialized in social sciences could understand it.

[15] Curiously enough, picture-based learning is also useful in studying anatomy. Students accustomed to rule-based learning typically learn anatomy in three steps: memorizing the name, memorizing the verbal (or written) description, and memorizing the connection between a name and the matching description. Thus, I once advised a student to memorize the name but associate it with the images of the anatomical object. As a consequence, his score soared dramatically from a meager 39% in the mid-term examination to 70% in the final examination.

[16] The adverb "fully" is used here twice only in a loose and relative sense. "Reasonably" would be a good substitute for the adverb "fully." Frankly, I do not think I fully understand what I think I have understood, and I never will for reasons that take an article as long as this one to explain. I am "fully" contended with the prospect of getting a better and better understanding as my age advances.

[17] "A Nation at Risk: the Imperative for Educational Reform," which contains the famed phrase "rising tide of mediocrity," was a report to the Nation and the then Secretary of Education, prepared by the National Commission on Excellence in Education, in April, 1983. It can be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC, 20402.

[18] Just imagine the formidable task of programming a digital computer to judge a Beauty Contest by purely objective (numerical) criteria.

[19] Right hemisphere also processes auditory patterns. Thus, picture-based learning may be generalized to "pattern"-based learning if musical activities are included in the discussion. Thus, when Mozart conceived Requiem, as depicted in the fictionalized movie "Amadeus," he conceived the tone pattern as a whole, with different voices and instruments all running in *parallel* (perhaps without going through visual imagery of imagined musical scores). But when he dictated the music at his deathbed to Antonio Salieri, a then respected and accomplished composer of no mean credentials, he did it sequentially for each voice and instrument part. Salieri was puzzled by his choices of notes at first, and then said, "yes, yes, yes." (Eureka!). Salieri certainly could perform pattern-based musical reasoning, he was simply slower and perhaps less creative than Mozart.

[20] According to the legend, Alexander Fleming's discovery of penicillin was attributed to *serendipity*. Although it is difficult for me to reconstruct Fleming's mind set without the help of his confession, I suspect Fleming must have in his mind, day and night whether awakened and dreaming, the imagery of a large number of bacterial colonies wiped out by the magic bullet he was searching. Thus, the moment he saw a bacterial culture dish ruined by a contamination, he recognized what he wanted. Louis Pasteur said, "...in fields of observation, chance favors only the prepared mind." Perhaps, by "prepared mind," Pasteur meant having the imagery of what you pursue held in your mind all the time in order to be ready for use as a "template" for matching on short notice. If so, then the word "dedication" acquires a new meaning.

[21] I am using the analogy between conceptualized information and rules on the one hand and compressed or zipped software programs on the other hand. Readers who are familiar with the function of software programs, PKZIP and PKUNZIP, will appreciate the analogy.

[22] Persons who really care about the validity of what's being learned often experience anxiety and mental distress unless one becomes fully convinced by logical reasoning.

[23] My misgiving about multiple choice exam questions implies that essay examination questions are the antidote. Unfortunately, that is not exactly a valid conclusion. Lately, I found some students

managed to memorize lengthy logical arguments of essay questions. Only an inadvertent "transposition" of two key sentences betrayed the practice. Nevertheless, essay exams make it easier to expose flaws in thought processes than multiple choice examinations.

[24] This is of course not strictly true because carrying out "canned" mathematical procedures often requires considerable mathematical dexterity and ingenuity of the individual.

[25] That both rule-based and picture-based reasoning are exploited by the human brain seems to be deeply rooted in the inherent nature of biological information processing. Reacting biomolecules in the water-filled cell (cytoplasm) resorts to an exploratory approach of random diffusion at large distances and to a more focused and deterministic approach by allowing short range intermolecular forces to guide it towards its target (molecular recognition). See a previous article "Mesoscopic processes in biocomputing: the role of randomness and determinism" in the back issue of 21st.

[26] According to Dean Simonton ("Scientific Genius: a Psychology of Science", Cambridge University Press, 1988, pp. 120-123), dogmatism is inversely related to creativity, and additional years of schooling beyond college juniors causes a decline in creativity and a rise in dogmatism. Presumably, excessive rule-based learning (indoctrination) is the culprit.

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